Engineering Fronts 2023

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Contents

Engineering Fronts

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 2023 Global Engineering Fronts research relies on the nine academic divisions and academic journals of the CAE to identify 93 engineering research fronts and 94 engineering development fronts, collaborating with Clarivate. 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, 28 key engineering research fronts and 28 key engineering development fronts are selected for detailed interpretations.

In 2023, 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 2023 project and comprises two parts. Part A explains the data and methodology. Part B presents 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; and (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 seven 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!

Part A 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 the capabilities for innovation in the field of engineering science and technology. According to the innovation stage of the front, engineering fronts are categorized into engineering research fronts which focuses on theoretical exploration and engineering development fronts which focuses on the practical application of engineering science and technology.

The Global Engineering Fronts 2023 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 2023, 93 engineering research fronts and 94 engineering development fronts are selected, with 28 engineering research fronts and 28 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 strategies 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 selection, 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

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	11	11
Energy and Mining Engineering	12	12
Civil, Hydraulic, and Architectural Engineering	10	10
Environmental and Light Textile Engineering	10	10
Agriculture	10	11
Medicine and Health	10	10
Engineering Management	10	10
Total	93	94

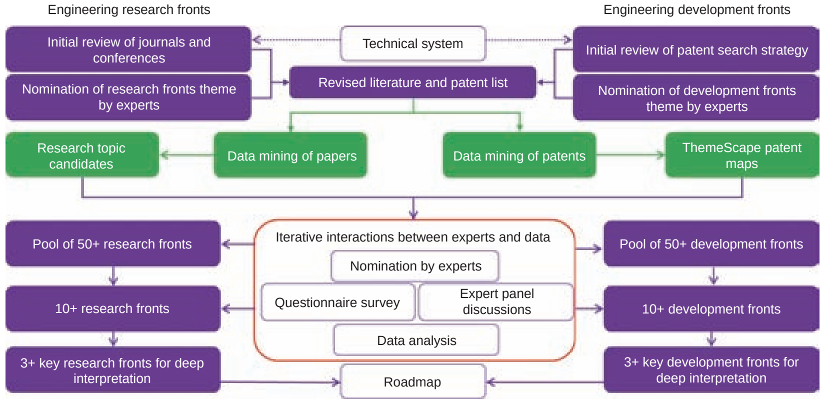

Figure 1.1 Operation procedure of the Global Engineering Fronts project

in Figure 1.1, in which the green, purple, and red boxes indicate the data analysis, expert research, and multi-round iterative interactions between experts and data, respectively.

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 93 engineering research fronts in the nine fields.

1.1 Acquisition and preprocessing of paper data

Firstly, the mapping relationship between the technology systems of the nine academic divisions of the CAE and Web of Science disciplines was constructed, and the lists of academic journals and academic 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 12 696 journals and 54 389 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 2023). 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 1.1.1.

Table 1.1.1 Overview of data sources in each field

No.	Field	Number of journals	Number of conferences	Number of top high-impact papers
1	Mechanical and Vehicle Engineering	547	3 325	112 450
2	Information and Electronic Engineering	1 010	22 572	228 672
3	Chemical, Metallurgical, and Materials Engineering	1 235	4 850	310 860
4	Energy and Mining Engineering	946	2 893	160 920
5	Civil, Hydraulic, and Architectural Engineering	406	1 428	104 330
6	Environmental and Light Textile Engineering	1 371	1 645	245 146
7	Agriculture	1 463	1 282	190 750
8	Medicine and Health	4 890	14 887	524 174
9	Engineering Management	828	1 507	60 673

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 2017–2020 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 2021–2022 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, 756 clustered literature topics in the nine fields were obtained (Table 1.2.1).

Table 1.2.1 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	12 404	49 484	98
2	Information and Electronic Engineering	23 529	101 924	68
3	Chemical, Metallurgical, and Materials Engineering	30 400	122 129	66
4	Energy and Mining Engineering	17 173	71 528	89
5	Civil, Hydraulic, and Architectural Engineering	11 051	46 128	129
6	Environmental and Light Textile Engineering	25 575	101 630	89
7	Agriculture	19 645	76 697	76
8	Medicine and Health	52 636	215 909	66
9	Engineering Management	6 137	23 325	75

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.

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, approximately 10 engineering development fronts were identified in each field.

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 2017 and 2022; the cut-off date of the citations was January 2023. 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.

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.

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.

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 2023 project conducted detailed analysis on the development focuses and trends of key engineering research fronts and 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.

4 Terminologies

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

High-impact papers: Papers that rank 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.

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

Mean publication 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 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.

Part B Reports in Different Fields

I. Mechanical and Vehicle Engineering

1 Engineering research fronts

1.1 Trends in 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 (as listed in Table 1.1.1). Among these, “low-carbon and zero-carbon fuel engine technologies”, “flexible self-powered wearable sensors”, “multi-material 4D printing”, “state-of-the-art vascular robotic system development”, “transfer learning-based machine fault diagnosis”, and “robot-assisted milling and polishing” are extensively studied traditional topics. “Dynamically reconfigurable mobile micro-robot swarms”, “intelligent performance test for automatic driving in an adversarial environment”, and “wireless charging system for underwater autonomous vehicles” are considered as emerging topics. The annual number of core papers published during the years 2017–2022 is listed in Table 1.1.2.

(1) Hypersonic flight vehicle technology

Hypersonic aircraft refer to aircraft that can fly in the atmosphere at speeds exceeding Mach 5. Compared with traditional subsonic, supersonic, and supersonic aircraft, hypersonic aircraft have high speeds, fast response capabilities, and high penetration success rates. They are also hard to intercept. Moreover, hypersonic aircrafts have tremendous military and potential economic value. The development of a hypersonic vehicle technique involves multiple disciplines, such as high-speed aerodynamics, computational fluid dynamics, high-temperature gas dynamics, chemical dynamics, guidance and control, electronics, and material and structure fabrication. In their more than half a century of development, hypersonic

Table 1.1.1 Top 10 engineering research fronts in mechanical and vehicle engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Hypersonic flight vehicle technology	50	4 930	98.60	2018.7
2	Low-carbon and zero-carbon fuel engine technologies	47	4 429	94.23	2018.8
3	Dynamically reconfigurable mobile micro-robot swarms	11	870	79.09	2019.1
4	Flexible self-powered wearable sensors	30	2 218	73.93	2019.8
5	Intelligent performance test for automatic driving in an adversarial environment	11	337	30.64	2019.7
6	Multi-material 4D printing	32	736	23.00	2020.4
7	Wireless charging system for underwater autonomous vehicles	13	337	25.92	2020.2
8	State-of-the-art vascular robotic system development	18	377	20.94	2020.3
9	Transfer learning-based machine fault diagnosis	12	328	27.33	2021.0
10	Robot-assisted milling and polishing	41	1 717	41.88	2019.9

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in mechanical and vehicle engineering

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Hypersonic flight vehicle technology	13	13	9	9	4	2
2	Low-carbon and zero-carbon fuel engine technologies	5	19	7	12	3	1
3	Dynamically reconfigurable mobile micro-robot swarms	1	2	4	3	1	0
4	Flexible self-powered wearable sensors	2	4	8	4	9	3
5	Intelligent performance test for automatic driving in an adversarial environment	1	2	2	1	4	1
6	Multi-material 4D printing	4	1	1	4	16	6
7	Wireless charging system for underwater autonomous vehicles	1	3	0	1	5	3
8	State-of-the-art vascular robotic system development	0	2	4	3	4	5
9	Transfer learning-based machine fault diagnosis	0	0	0	2	8	2
10	Robot-assisted milling and polishing	3	3	9	11	11	4

vehicle techniques have achieved great success in missile weaponry but slight progress in reusable launch vehicles and aircraft. The major challenges focus on four aspects. The first aspect is the development of a new theory and technique to design new configuration with a high lift-to-drag ratio and a high payload-to-structural weight fill-in ratio under a wide-speed band. The second is to develop new propulsion system in addition to scramjet engines that work well in high-speed conditions. This new system may be the new technology that combines aero-engines and ramjets. The third is to develop extremely high-temperature resistant materials and thermal protection cooling systems and methodologies. The fourth aspect involves control and navigation systems. The complicated environment and extremely hard work states demand cutting-edge techniques for control and navigation systems. Analysis shows that the above four research directions are the key to developing reusable hypersonic launch, hypersonic aircraft, and ground take-off for space flight vehicles.

(2) Low-carbon and zero-carbon fuel engine technologies

Low-carbon and zero-carbon fuel engine technologies refer to the use of fuels with low or zero carbon content to partially or fully replace conventional high-carbon-content gasoline, diesel, and other fuels, with the goal of reducing the specific carbon dioxide emissions of engines from the source. It involves the cross-integration of power engineering and engineering thermophysics, energy science and technology, chemistry and chemical engineering, traffic and transportation engineering, materials science and engineering, and other disciplines. Related research includes the manufacturing of various low-carbon and zero-carbon fuels, their safe onboard storage and delivery, clean and effective utilization through novel engine combustion modes and control, and the analysis and optimization of their full life cycle carbon emissions. At present low-carbon and zero-carbon fuels that have received extensive public and research attention include natural gas, biomass-derived methanol, ethanol, dimethyl ether and biodiesel, green hydrogen, green ammonia, and e-fuel, which are synthesized using renewable electricity. Significant technological advancements of low-carbon and zero-carbon engines have been achieved in recent years. Various companies and research institutions have developed prototype engines that can run using carbon-free fuels, including hydrogen and ammonia. Future research directions will focus on the development of novel engine combustion and emission control technologies that can further increase the thermal efficiency of engines running on low-carbon and zero-carbon fuels while approaching zero pollutant emissions. Meanwhile, with the continuous development of renewable electricity, efficient and low-cost production of biofuel, green hydrogen, ammonia, and other related technologies, the use of low- and zero-carbon fuels in engines will eventually become widespread.

(3) Dynamically reconfigurable mobile micro-robot swarms

A mobile micro-robot swarm refers to an autonomous task execution swarm in which a large number of dispersed, low-cost isomorphic/heteromorphic autonomous mobile micro-robot individuals with local perception, decision-making, and action capabilities are self-organized according to the task objectives in wide-area and complex task scenarios by means of the mechanisms of information interaction, cooperation, and coordination among the individuals. A micro-robot swarm is characterized by a stable and orderly topology, individual coordination and collaboration, a consistent behavioral goal, and mutually complementary functions. Dynamic reconfigurability indicates the ability of a mobile micro-robot swarm to dynamically change its composition, topology, coordination relationships, and individual task loads according to changes in mission objectives, capability requirements, mission execution states and situations, environmental events, individual robots' capabilities and others uncertainties to quickly respond to changes in the swarm and in the environment. A dynamically reconfigurable mobile micro-robot swarm is a vivid reflection and physical embodiment of a multiagent system with self-organization, self-adaption, and intelligence emergence characteristics, involving not only individual intelligence (autonomous control, autonomous perception, autonomous planning, and autonomous decision making) but also a swarm-level architecture, communication network, coordination mechanism, information fusion, state estimation, task allocation, path planning, formation control, multiagent consistency, and other multilevel, multifaceted theories and technologies. A dynamically reconfigurable mobile micro-robot swarm is also an advanced form of multi-robot system collaborative control technology. Traditional multi-robot cooperative control is usually realized through the use of a centralized control and global coordination mode, incurring difficulties in swarm scale, coordination efficacy, and expandability. Dynamically reconfigurable mobile micro-robot swarms are significantly different from traditional multi-robot cooperative control technology in terms of the number of robots involved, complexity of tasks, environment, and division of labor and collaboration as well as self-adaptation and robustness to tasks, environmental events, and so on. Furthermore, adapting existing technology to the development requirements of dynamically reconfigurable mobile micro-robot swarms is difficult. The swarming behaviors of many swarming animals in nature can serve as an inspiration for the development of dynamically reconfigurable mobile micro-robot swarms. Exploring the emergence mechanisms of swarm intelligence in swarming animals and mapping it into the field of control of dynamically reconfigurable mobile micro-robot swarms and constructing a task-oriented self-organization-based dynamically reconfigurable architecture and self-organized collaboration mechanism based on localized information propagation under complex and restricted communication conditions. Control of key technologies such as the wide-area, distributed collaborative dynamic allocation of large-scale swarm multimodal tasks; large-scale multisource heterogeneous information fusion and decentralized situational awareness under weak communication conditions; path planning and replanning, considering dynamics; formation dynamic control, including motion uncertainty information and event-triggered multi-robot coherent tracking; and so on is the key direction and a research hotspot for the development of dynamically reconfigurable mobile micro-robot swarms.

(4) Flexible self-powered wearable sensors

A flexible self-powered wearable sensor refers to a specialized device that can be attached to the surface of the human body. Its main function is to collect and monitor physiological parameters or environmental information relevant to the human body. A distinguishing characteristic of this sensor is its inherent capability to generate power autonomously, eliminating the need for an external power source. This self-powering feature contributes significantly to the sensor's capacity to ensure wearer comfort and convenience during usage. Typically, such sensors are fabricated using flexible materials, enabling them to accommodate various body shapes and movements effectively. The key innovation lies in the incorporation of energy harvesting technology, which empowers the sensor to derive power from bodily motions or alternative ambient energy sources, such as light or temperature gradients. This self-sustaining mechanism obviates the reliance on conventional batteries or external power supplies, enhancing the overall efficiency and practicality of the wearable sensor. Flexible self-powered technology enables the conversion of micro-energy from the human body and the surrounding environment into electric energy. This technology provides active wearable sensors for human physiological and motion monitoring or prolonged working life for wearable sensors. Energy harvesting and conversion methods for flexible self-powered wearable sensors primarily encompass electromagnetic, piezoelectric, triboelectric, photovoltaic, thermoelectric, and others. Relevant research principally involves three aspects. The first one is the study of mechanisms, materials, structures, and performance enhancement for energy conversion. This study includes the development of energy harvesting devices that can be flexibly attached to the human body to enhance energy conversion efficiency. The second aspect is the combination of various environmental energy collection methods to design and fabricate flexible composite energy harvesting systems, thereby optimizing the environmental energy utilization efficiency. The third one is the energy management and signal processing technologies used to develop integrated flexible circuits to improve the utilization rate of electric energy, including the sensitivity and accuracy of active wearable sensors. Flexible self-powered wearable sensors provide an attractive direction for the development of wearable electronics with their capabilities for environmental energy harvesting, active sensing, and miniature integration. These capabilities represent the development trend of self-powered technology and body area networks, with broad application prospects in fields such as motion sensing, health monitoring, and personalized medicine.

(5) Intelligent performance test for automatic driving in an adversarial environment

An intelligent performance test for automatic driving in an adversarial environment is the key technology and means for solving the intelligent research and development, training, evaluation, rating, and verification of vehicles, ships, and other modes of transportation. Virtual simulation, scaled model, scenario test, and real vehicle/ship test are the basic methods for traditional autonomous driving testing. However, with the enhancement of digital twin technology and the evolution of sensor communication technology, a single-mode test method can no longer meet the requirements of intelligent performance testing in terms of environmental consistency, effectiveness, and repeatability. Virtual–real fusion testing that emphasizes mapping, interaction, linkage, and complementarity between digital space and physical space has become a research hotspot in intelligent performance testing. In particular, under the premise of ensuring safety and efficiency in intelligence testing, determining how to reflect game, confrontation, and cooperation between agents and between agents and humans and building an adversarial test environment are extremely important fundamental problems that are worthy of attention. Theories and methods of testing and evaluation, driving performance test and evaluation, safety test and evaluation, reliability test and evaluation, comprehensive tests, test tool chain design, and other issues are currently the major research hotspots in this field. Systems engineering concepts (e.g., model-based systems engineering, model-based design, digital twins, and cyber–physical systems), modeling and simulation technologies that are relevant to intelligent performance test are also receiving increasing attention.

(6) Multi-material 4D printing

Multi-material 4D printing is a technology that utilizes additive manufacturing processes to create intelligent components with "stimulus–response" characteristics. The stimuli mainly originate from external energy fields, such as heat, electricity, magnetism and light, and the response manifests as controllable changes in the shape, properties, or functionalities of the components over time. Traditional single-material additive manufacturing has encountered significant challenges in meeting the demands of high-end manufacturing industries for property, functionality, and their dynamic variations. Consequently, the integration of materials, structures, and functionalities in multi-material 4D printing has become a cutting-edge technology. This involves distributing different materials to designated regions and achieving predetermined changes in structures and properties through external stimuli. The inherent self-sensing and self-driven qualities of such components hold immense potential for aerospace deployable structures, biomedical scaffolds, and other critical applications. The current research focus in this field includes intelligent component design and topology optimization, the development of new 4D printing processes, numerical simulations and path planning for the printing process, micro/nano-level multi-material 4D printing, metamaterial printing, characterization methods for intelligent component property and its variations, and the regulation and optimization of multi-material interface properties. There is also increasing interest in designing intelligent components with various responses under multiple energy fields and their multi-material 4D printing, alongside high-precision and high-efficiency multi-material printing.

(7) Wireless charging system for underwater autonomous vehicles

Power endurance and sustainability are important indices for measuring the performance of underwater autonomous vehicles, mainly depending on the energy storage capacity of the onboard energy system. The method of recovering vehicles and quickly replacing their modular energy system suffers from high cost, inefficiency, and poor concealment. Underwater wireless charging technology has become a key landmark technology for enhancing the power endurance and sustainability of underwater autonomous vehicles because it achieves energy transmission through a non-contact method, which has the advantages of high safety and strong environmental adaptability. Wireless charging technology can be classified into magnetic field, electric field, microwave, laser, and ultrasonic modes according to the power transfer mechanism. Considering the complexity of the underwater environment and the particularity of the transmission medium, the magnetic field mode is considered as one of the optimal schemes for underwater charging due to its unique advantages in the principle and structure of power transmission, with significant advantages in the wireless charging process of underwater autonomous vehicles. In the principle design and engineering practice of underwater charging systems, the design of the magnetic coupling mechanism, seawater medium energy transmission and eddy current loss characteristics, bidirectional energy transmission circuit topology and control strategy, underwater bidirectional energy, and information synchronous transmission technology are the popular topics on underwater wireless charging technology.

(8) State-of-the-art vascular robotic system development

Vascular diseases have emerged as a primary threat to human health. Vascular robotic systems can offer valuable support to interventionalists during vascular interventions, such as enhancing precision, minimizing radiation exposure, and reducing workload. However, most existing vascular robotic systems use a master–slave control paradigm, where tool delivery at the slave end relies entirely on the master's instructions. These systems lack expert-level capabilities in intelligent analysis, decision-making, and manipulation, and thus, they fail to provide effective intelligent assistance to interventionalists and restrict their widespread application. To enhance the intelligence of vascular robotic systems, key challenges, such as autonomous image navigation, active force perception, and expert skill learning, must be addressed. These challenges encompass frontier issues, such as vessel segmentation in surgical images, detection and localization of interventional tools, preoperative/intraoperative multimodal image registration, modelling tool–vessel interaction, tactile perception and feedback, manipulation skill modeling and learning, and human–robot intelligent collaboration. Moreover, focus has been increasing on the mechanism design for collaborative multi-tool delivery, intelligent multi-tool control, and precise quantitative delivery in robot-assisted intervention for complex vascular lesions.

(9) Transfer learning-based machine fault diagnosis

Transfer learning refers to the process of applying knowledge learned in one field to another. In the context of fault diagnosis, transfer learning involves using diagnostic methods validated in simulations or laboratory settings. This means that insights gained in a digital or semi-physical space can be leveraged in the actual physical space. Transfer learning can be accomplished through feature- and model-based transfer, which involve techniques, such as enhancement and fine-tuning. These methods aim to enhance the consistency of samples between the source domain and the target domain, thus reducing the disparity during the transfer process. Consequently, they improve the decision accuracy and scene generalization performance of fault diagnosis models, particularly when working with limited data and varying operating conditions. Transfer learning proves especially crucial in fault diagnosis for large complex equipment, such as aircraft engines, aerospace engines, nuclear power equipment, and space station operation equipment. In such cases, obtaining real fault samples is difficult due to the destructive nature of the faults. Transfer learning is expected to offer substantial benefits in these scenarios. Research on the theory and application of transfer learning to fault diagnosis represents the current hotspots and challenges in this field. Similar to how jade can be polished using stones from other hills, transfer learning has the potential to enhance the effectiveness of fault diagnosis for major equipment.

(10) Robot-assisted milling and polishing

Robot-assisted milling and polishing is a method of using the flexibility and reconfigurability of robots to achieve high-efficiency, high-quality, and stable machining of large and complex components in the major equipment of strategic industries, including aviation, aerospace, and navigation. Large and complex components have characteristics such as large size, complex surface, and strict requirements of shapes and dimensions, and the high-performance manufacturing of these components is a recognized international problem. Traditional manufacturing mostly uses equipment such as machine tools and machining centres, which have small travel distance and insufficient mobility. The machining of large structural parts requires multiple segmentations and slicing, which result in low manufacturing efficiency. At the same time, the process of polishing relies heavily on manual operations, resulting in inconsistent machining accuracy. Moreover, the generation of polishing dust damages the operators' health. Robot-assisted machining has the characteristics of flexible large-space manufacturing, good reconfigurability, and easy integration and coordination. It can transform the manufacturing mode for large and complex structures and shows great application potentials in fields such as aircraft structural parts milling, large wind turbine blades, and high-speed rail body polishing. The main research hotspots in this field are the precision control of large components, the machining mechanism of robot-assisted milling and polishing, the innovative design of machining robot system, and the integration of multi-robot collaborative measurement-modeling-machining.

1.2 Interpretations for three key engineering research fronts

1.2.1 Hypersonic flight vehicle technology

The research on hypersonic flight vehicle technology can be traced back to the development of hypersonic gliders in the 1950s. Since the late 1990s, hypersonic flight vehicle techniques have become the research focus in several science and technology powerhouses as the scramjet technology matures. Several nations have successfully conducted experiments and flight tests, and some have used hypersonic missiles in practical missions.

The next generation of flight vehicles calls for the capability to reach any corner on earth within an hour, fast penetration ability, and launch vehicle reusability from ground to space. The hypersonic vehicle technology facilitates the objectives. Compared with traditional aircraft, hypersonic vehicles work in extremely complex environments, flights with wide speed bands, and large altitude ranges. They experience an extremely complicated flow field, and aerodynamic heating produces extremely high temperatures in the boundary layer. The combined effects make designing aerodynamic configurations and vehicle structure layouts extremely difficult. Moreover, cutting-edge propulsion techniques are required. The vehicle body structure is strongly coupled with the propulsion system. High nonlinearity and big uncertainty exist in the flight vehicle model. Thus, high accuracy in control and terminal guidance is very hard to obtain. Hypersonic aircraft technology has become a hot research frontier in the 21st century. The major challenges focus on four aspects. The first aspect involves studying the principle combining the wave rider and lift body theory to develop a configuration with a high lift-to-drag ratio. This aspect also involves studying AI-based optimization methods for lightweight structures and structures with high payload-to-vehicle fill-in ratios. The second aspect includes developing a new propulsion engine, investigating new methods to utilize the advantages of aero-engines and ram jets, studying techniques for variable sizes of engine burners, and developing adjustable flame stabilization devices. The third aspect involves studying extremely high-temperature-resistant composite material systems and ablative heat protection methods, constructing high-accuracy flow models in ablation and detachment processes, and developing accurate simulation methods and experimental test approaches. The fourth aspect includes studying the methodology for an accurate flight control dynamic model, deriving a robust intelligent control strategy to handle strong interferences and big uncertainties, and developing high-accuracy terminal guidance techniques in the hypersonic flight phase. The study in above aspects lays the foundation for developing hypersonic flight vehicle theory and technology, and is of great practical significance for China to achieve a strong aerospace force and move toward an aerospace powerhouse.

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 USA, Canada, and Singapore, as shown in Table 1.2.1. Among the Top 10 countries with the most published papers, China has the most collaboration with UK, Canada, and Singapore, as shown in Figure 1.2.1. Institution with the highest number of core papers published is Northwestern Polytechnical University. The institutions with the highest citations per paper are Concordia University, National University of Singapore, and Tsinghua University, as shown in Table 1.2.2. As shown in Figure 1.2.2, Northwestern Polytechnical University and Tsinghua University have the most collaboration. The top country for citing papers is China, as shown in Table 1.2.3. The Top 3 output institutions for citing papers are Northwestern Polytechnical University, Harbin Institute of Technology, and Beihang University, as shown in Table 1.2.4. Figure 1.2.3 shows the roadmap of the engineering research front of "hypersonic flight vehicle technology".

Table 1.2.1 Countries with the greatest output of core papers on "hypersonic flight vehicle technology"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	43	86.00	4 183	97.28	2018.6
2	USA	4	8.00	609	152.25	2018.2
3	UK	4	8.00	384	96.00	2019.2
4	Canada	3	6.00	439	146.33	2017.7
5	Singapore	3	6.00	436	145.33	2017.3
6	Iran	3	6.00	217	72.33	2019.3
7	Republic of Korea	3	6.00	183	61.00	2020.0
8	Azerbaijan	2	4.00	159	79.50	2018.5
9	India	1	2.00	125	125.00	2020.0
10	Australia	1	2.00	63	63.00	2021.0

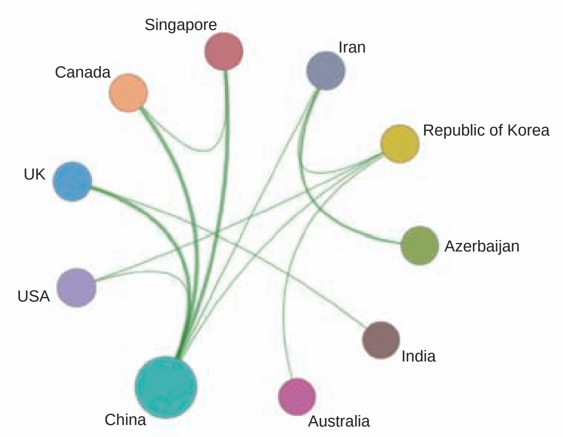

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "hypersonic flight vehicle technology"

Table 1.2.2 Institutions with the greatest output of core papers on "hypersonic flight vehicle technology"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Northwestern Polytechnical University	12	24.00	1 166	97.17	2018.8
2	National University of Defense Technology	7	14.00	761	108.71	2018.7
3	Harbin Institute of Technology	6	12.00	601	100.17	2019.0
4	Beihang University	6	12.00	422	70.33	2018.0
5	Tsinghua University	5	10.00	602	120.40	2018.4
6	Chinese Academy of Sciences	5	10.00	537	107.40	2020.0
7	Air Force Engineering University	5	10.00	374	74.80	2018.8
8	Beijing Institute of Technology	3	6.00	192	64.00	2019.7
9	Concordia University	2	4.00	353	176.50	2017.5
10	National University of Singapore	2	4.00	257	128.50	2017.5

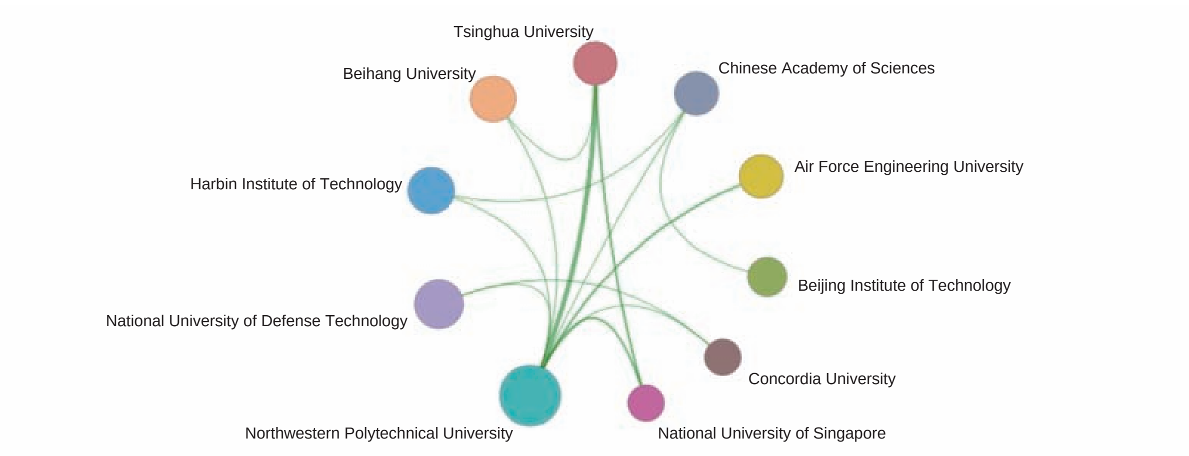

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "hypersonic flight vehicle technology"

Table 1.2.3 Countries with the greatest output of citing papers on "hypersonic flight vehicle technology"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	4 978	70.63	2020.7
2	USA	485	6.88	2020.6
3	India	311	4.41	2021.0
4	UK	258	3.66	2020.6
5	Iran	222	3.15	2020.7
6	Republic of Korea	192	2.72	2020.9
7	Australia	141	2.00	2020.7
8	Canada	135	1.92	2020.5
9	Russia	128	1.82	2020.6
10	Italy	106	1.50	2020.9

Table 1.2.4 Institutions with the greatest output of citing papers on “hypersonic flight vehicle technology”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Northwestern Polytechnical University	615	20.56	2020.6
2	Harbin Institute of Technology	450	15.05	2020.6
3	Beihang University	356	11.90	2020.8
4	Nanjing University of Aeronautics and Astronautics	319	10.67	2020.6
5	National University of Defense Technology	308	10.30	2020.7
6	Chinese Academy of Sciences	272	9.09	2020.6
7	Beijing Institute of Technology	186	6.22	2020.9
8	Southeast University	132	4.41	2020.3
9	Tianjin University	126	4.21	2020.1
10	Xi’an Jiaotong University	115	3.84	2021.0

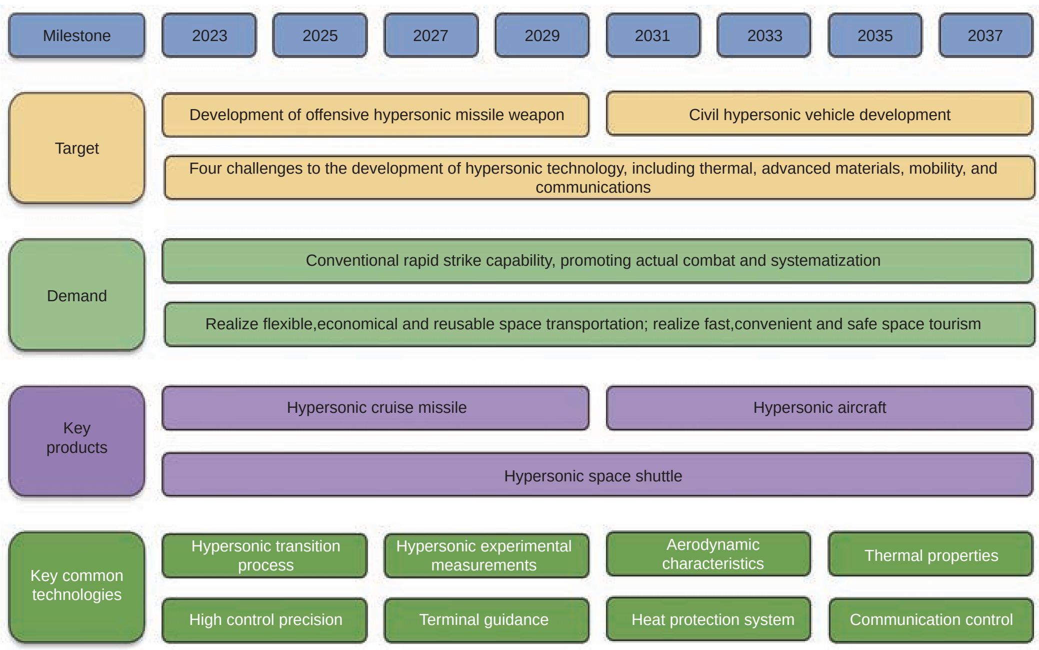

Figure 1.2.3 Roadmap of the engineering research front of “hypersonic flight vehicle technology”

1.2.2 Low-carbon and zero-carbon fuel engine technologies

Combustion engines are the primary power sources for road and maritime transport, off-road construction, agricultural machineries, and national defense equipment in our country. At present, most combustion engines use petroleum gasoline and diesel as fuel. While providing the necessary power, these engines emit a considerable amount of CO_2 into the atmosphere. Statistics indicate that carbon emissions from the transportation industry accounts for 10% of all carbon emissions in the country. Under the background of the “dual carbon” strategy, reducing and finally achieving zero engine carbon emissions through technological innovations is an imperative task. This goal is a prerequisite for the existence and sustainable development of combustion engines and related industries. Two technological routes are available for low-carbon engines: ① further increasing the thermal efficiency of conventional engines to reduce their specific fuel consumption, and ② partially or fully substituting conventional high-carbon-content gasoline and diesel fuels with new low-carbon-content fuels to stop carbon emissions from the source. Zero-carbon engines can only be realized through the full adoption of carbon-free or carbon-neutral fuels.

Increasing the thermal efficiency of conventional gasoline and diesel engines cannot only reduce specific carbon emissions but also help increase fuel economy. Therefore, this issue has always been the focus of research and development. For diesel engines, technological pathways for increasing thermal efficiency include boosting fuel injection pressure, compound turbocharging, exhaust heat recovery, and smart control. For gasoline engines, gasoline direction injection, variable compression ratio, stratified lean burn, gasoline compression ignition, electrification, and novel thermodynamic cycle are potential technologies for high-efficiency enablers. Zero-carbon fuels that can be used in engines are mostly hydrogen and ammonia, while life cycle carbon-neutral fuels include biomass-derived methanol, ethanol, dimethyl ether and biodiesel, and e-fuel, the latter of which are synthesized using renewable electricity combined with CO_2 captured from the air. Although carbon element is present in many carbon-neutral fuels and its combustion in engines will surely emit CO_2, its synthesis consumes CO_2, such that carbon neutrality can be achieved through the whole life cycle of these fuels. Future research is expected to focus on two aspects: ① the development of high-efficiency and low-cost techniques for the large-scale manufacturing of various carbon-neutral fuels; and ② fuel design based on the complementary combustion features of various carbon-neutral fuels, which will support the realization of zero-carbon emission engines when combined with the development of novel combustion and emission control techniques.

The combustion of hydrogen and ammonia does not produce any CO_2 emissions, and engines powered by these carbon-free fuels have been a research focus in recent years. Hydrogen engines mostly employed a spark ignition mode, and major research directions include techniques to avoid flashback and knocking, NO_x emission mitigation techniques, and safe and efficient onboard hydrogen storage methods. Considering the low reactivity and low flame speed of ammonia, achieving its stable combustion across all engine conditions is challenging. Current strategies primarily include mixing ammonia with more reactive fuels, such as natural gas, gasoline, and diesel. The co-combustion of ammonia and hydrogen is also possible, with the potential of obtaining the required hydrogen from the onboard cracking of ammonia. Future research is expected to focus on high-efficiency and clean combustion modes for ammonia, highly effective onboard selective catalytic reduction, and ammonia cracking systems.

Low-carbon and zero-carbon fuel engine technology involves the fields of power engineering and engineering thermophysics, energy science and technology, chemistry and chemical engineering, traffic and transportation engineering, materials science and engineering, and other related disciplines. It is a key technology for ensuring the achievement of the “dual carbon” strategy in the transportation industry and promoting the sustainable development of combustion engines and other related industries under the “dual carbon” background. It is an area of high research value and societal impact.

The top countries with the maximum number of core papers published in this front are China, UK, and India, and the countries with the highest citations per paper are Saudi Arabia, UK, and Canada, as shown in Table 1.2.5. China has the most collaboration with UK and with Ireland, as shown in Figure 1.2.4. Institutions with the maximum number of highest citations per paper are University of Oxford, Tsinghua University, and National Institute of Technology, as shown in Table 1.2.6. There is cooperation between Dalian Maritime University and Trinity College Dublin, as well as between Xi’an Jiaotong University and Beijing Institute of Technology. Cooperation also exists between Tsinghua University and the University of Oxford, as shown in Figure 1.2.5. The top country for citing papers is China, as shown in Table 1.2.7. The Top 3 output institutions for citing papers are Xi’an Jiaotong University, Chinese Academy of Sciences, and Beijing Institute of Technology, as shown in Table 1.2.8. Figure 1.2.6 shows the roadmap of the engineering research front of “low-carbon and zero-carbon fuel engine technologies”.

Table 1.2.5 Countries with the greatest output of core papers on "low-carbon and zero-carbon fuel engine technologies"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	16	34.04	1 755	109.69	2019.2
2	UK	10	21.28	1 294	129.40	2019.1
3	India	6	12.77	565	94.17	2019.2
4	USA	5	10.64	505	101.00	2019.8
5	Turkey	5	10.64	471	94.20	2019.0
6	Canada	4	8.51	462	115.50	2018.2
7	Norway	3	6.38	248	82.67	2020.0
8	Malaysia	3	6.38	215	71.67	2018.0
9	Ireland	3	6.38	184	61.33	2019.7
10	Saudi Arabia	2	4.26	326	163.00	2018.0

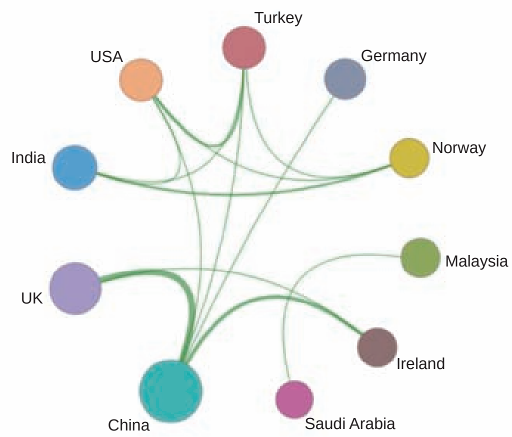

Figure 1.2.4 Collaboration network among major countries in the engineering research front of "low-carbon and zero-carbon fuel engine technologies"

Table 1.2.6 Institutions with the greatest output of core papers on "low-carbon and zero-carbon fuel engine technologies"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of Oxford	2	4.26	741	370.50	2018.5
2	Tsinghua University	2	4.26	722	361.00	2018.0
3	National Institute of Technology	2	4.26	229	114.50	2018.5
4	Sathyabama Institute of Science and Technology	2	4.26	178	89.00	2019.5
5	Xi'an Jiaotong University	2	4.26	155	77.50	2021.0
6	Dalian Maritime University	2	4.26	139	69.50	2020.5
7	Trinity College Dublin	2	4.26	139	69.50	2020.5
8	Beijing Institute of Technology	2	4.26	111	55.50	2020.0
9	Brunel University London	2	4.26	110	55.00	2017.5
10	University of Malaya	2	4.26	91	45.50	2018.0

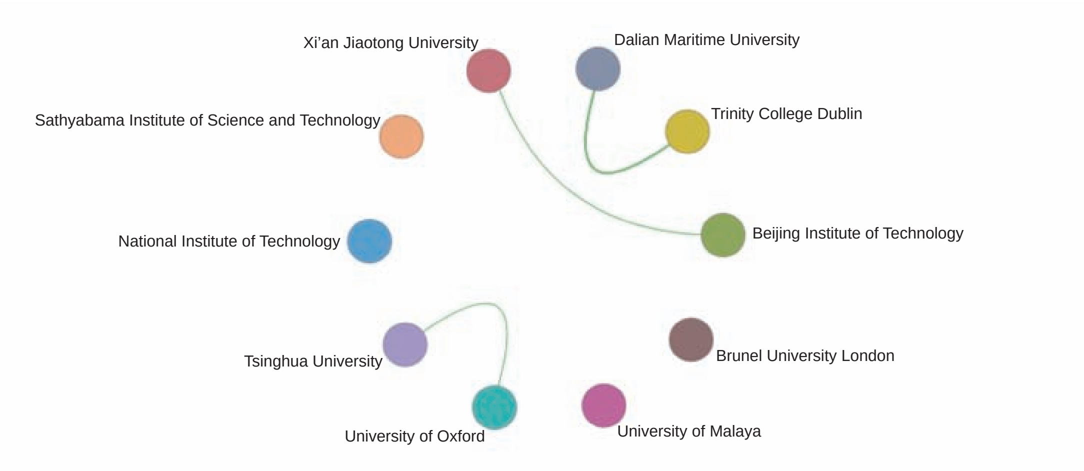

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "low-carbon and zero-carbon fuel engine technologies"

Table 1.2.7 Countries with the greatest output of citing papers on "low-carbon and zero-carbon fuel engine technologies"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 357	36.82	2021.2
2	India	545	14.79	2021.1
3	USA	356	9.66	2021.1
4	UK	304	8.25	2021.2
5	Italy	200	5.43	2021.0
6	Turkey	174	4.72	2021.1
7	Germany	171	4.64	2021.3
8	Republic of Korea	150	4.07	2021.5
9	Malaysia	146	3.96	2021.1
10	Saudi Arabia	142	3.85	2021.4

Table 1.2.8 Institutions with the greatest output of citing papers on "low-carbon and zero-carbon fuel engine technologies"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Xi'an Jiaotong University	102	12.59	2021.4
2	Chinese Academy of Sciences	96	11.85	2021.2
3	Beijing Institute of Technology	91	11.23	2021.1
4	Tianjin University	89	10.99	2021.2
5	Tsinghua University	88	10.86	2021.1
6	Shanghai Jiao Tong University	78	9.63	2021.3
7	Beijing University of Technology	69	8.52	2021.1
8	Jiangsu University	68	8.40	2020.8
9	Zhejiang University	46	5.68	2021.1
10	Sathyabama Institute of Science and Technology	42	5.19	2021.0

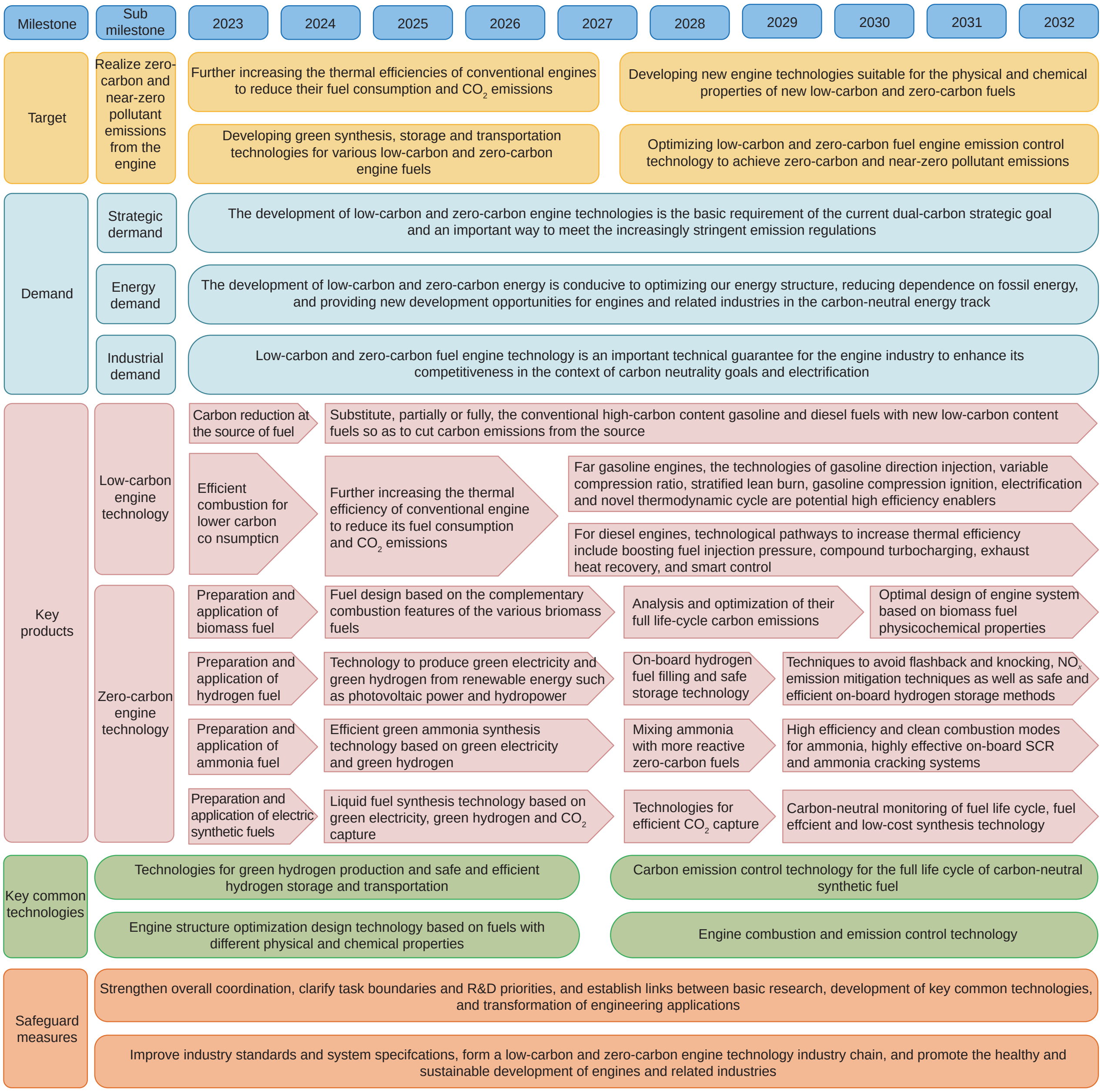

Figure 1.2.6 Roadmap of the engineering research front of “low-carbon and zero-carbon fuel engine technologies”

1.2.3 Dynamically reconfigurable mobile micro-robot swarms

As the application requirements of intelligent mobile robots expand toward the direction of complex multimodal tasks, three-dimensional wide-area operation, complex and changeable working environments, and interference and confrontation, meeting the functional and performance requirements of single complex and expensive robots has become difficult. The use of a large number of dynamically reconfigurable, and relatively low-cost isomorphic/heterogeneous autonomous mobile micro-robots to form a task execution swarm, giving full play to the advantages of group division of labor, can not only improve the efficiency and robustness of task completion in complex environments but also reduce the cost of developing special complex system equipment and obtain significant economic benefits. Dynamically reconfigurable mobile micro-robot swarms have become an important development direction in the field of intelligent mobile robots and have broad application prospects in intelligent manufacturing factories, area coverage exploration, wide-area target search, and military operations.

Dynamically reconfigurable mobile micro-robot swarms include aerial intelligent unmanned aerial vehicle swarms, ground mobile robot swarms, water surface and underwater unmanned vehicles, and other forms, as well as the mixed swarms of the aforementioned forms. The individual robots in a swarm can be isomorphic or heterogeneous. The overall behavior of a dynamically reconfigurable mobile micro-robot swarm derives from the mutual coordination and cooperation of the individual robots with autonomous abilities based on the task goal, which is a vivid reflection and physical embodiment of the self-organization, self-adaptability, and intelligence emergence of a multiagent system and an advanced form of the collaborative control technology of a multi-robot system.

Dynamically reconfigurable mobile micro-robot swarm technology involves not only individual intelligence (autonomous control, autonomous perception, autonomous planning, and autonomous decision-making) but also multilevel and multifaceted theories and technologies such as a swarm architecture, communication network, coordination mechanism, information fusion, state estimation, task assignment, path planning, formation control, and multiagent consistency at the swarm level. Traditional multi-robot cooperative control mainly involves a hierarchical control architecture, strongly connected communication network, collaboration and coordination based on global information, centralized task allocation and scheduling, and pilot-following formation control. Improving a swarm's scale, collaborative efficiency, and scalability is difficult, and a swarm's scale is generally limited to several dozens of individuals. A dynamically reconfigurable mobile micro-robot swarm usually has a number of individuals reaching several hundred or several thousand or more, and the requirements for complex tasks, environments, division of labor and cooperation as well as adaptability and robustness to tasks and environmental events are significantly different from those of traditional multi-robot cooperative control technology. Meeting the development requirements of dynamically reconfigurable mobile micro-robot swarms is difficult for existing collaborative technology; thus, swarm theory and technology breakthroughs are urgently needed.

Modern biological studies revealed that some typical swarming animals, such as birds, fish, ants, wolves, and so on, can perceive the situation of and changes in the swarm and make decisions that are consistent with the behavioral goals of the swarm by using only the local information of the swarm and information of several neighboring individuals, thereby facilitating the emergence of the overall behavior of the swarm. Animal swarm behavior can serve as an inspiration and reference for the development of dynamically reconfigurable mobile micro-robot swarms. The intelligence emergence mechanism of swarm animals should be explored and mapped in the field of swarm control of dynamically reconfigurable mobile micro-robots, and a task-oriented dynamically reconfigurable architecture based on self-organization and a self-organization cooperation mechanism based on local information propagation under complex limited communication conditions should be built. Control of key technologies such as the dynamic assignment of large-scale distributed cooperative tasks in wide-area swarms; large-scale multisource heterogeneous information fusion and decentralized situation awareness under weak communication conditions; path planning and replanning, considering dynamic characteristics; dynamic formation control, including motion uncertainty information and event-based multi-robot consistency tracking; and so on has become a research hotspot for the development of dynamically reconfigurable mobile micro-robot swarms.

The top country with the maximum number of core papers published in this front is China, and the country with the highest citations per paper is USA, as shown in Table 1.2.9. Collaboration exist between China and USA, as well as between China and Switzerland. Collaboration can also be found between Germany and Turkey, as shown in Figure 1.2.7. Institution with the maximum number of highest citations per paper is the Chinese University of Hong Kong, and the top three institutions with the highest citations per paper are Beijing Institute of Technology, Michigan State University, and Harbin Institute of Technology, as shown in Table 1.2.10. Collaboration exists between Harbin Institute of Technology, Beijing Institute of Technology, and Michigan State University. Koç University and Max Planck Institute for Intelligent Systems also have a collaboration. The Chinese University of Hong Kong has collaboration with Chinese Academy of Sciences, University of Missouri, the Hong Kong Polytechnic University, and Shenzhen Institute of Artificial Intelligence and Robotics Society (wherein Chinese Academy of Sciences collaborates with University of Missouri), as shown in Figure 1.2.8. The top country for citing papers is China, as shown in Table 1.2.11. The Top 3 output institutions for citing papers are the Chinese University of Hong Kong, Chinese Academy of Sciences, and Harbin Institute of Technology, as shown in Table 1.2.12. Figure 1.2.9 shows the roadmap of the engineering research front of “dynamically reconfigurable mobile micro-robot swarms”.

Table 1.2.9 Countries with the greatest output of core papers on “dynamically reconfigurable mobile micro-robot swarms”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	10	90.91	803	80.30	2019.1
2	USA	2	18.18	330	165.00	2018.0
3	Germany	1	9.09	67	67.00	2019.0
4	Turkey	1	9.09	67	67.00	2019.0
5	Switzerland	1	9.09	10	10.00	2021.0

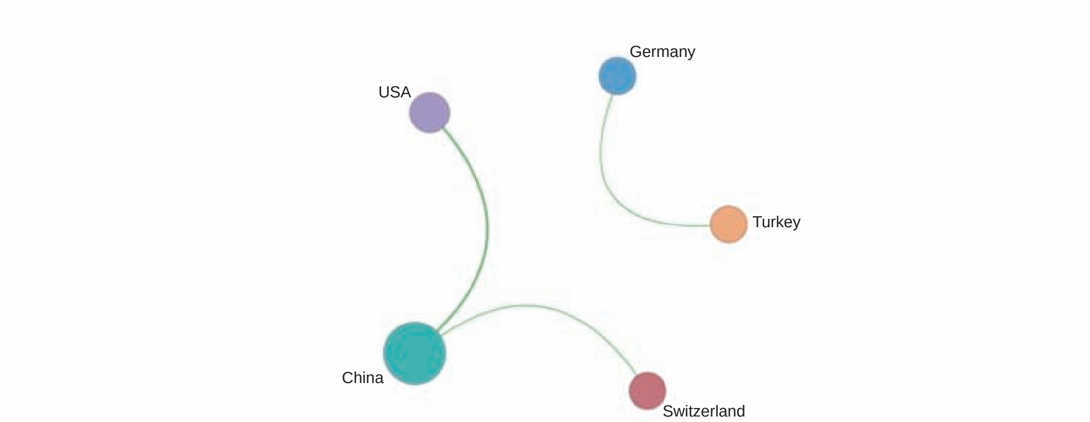

Figure 1.2.7 Collaboration network among major countries in the engineering research front of “dynamically reconfigurable mobile micro-robot swarms”

Table 1.2.10 Institutions with the greatest output of core papers on "dynamically reconfigurable mobile micro-robot swarms"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	The Chinese University of Hong Kong	8	72.73	516	64.50	2019.1
2	Harbin Institute of Technology	2	18.18	287	143.50	2019.0
3	Beijing Institute of Technology	1	9.09	262	262.00	2019.0
4	Michigan State University	1	9.09	262	262.00	2019.0
5	Chinese Academy of Sciences	1	9.09	68	68.00	2017.0
6	University of Missouri	1	9.09	68	68.00	2017.0
7	Koç University	1	9.09	67	67.00	2019.0
8	Max Planck Institute for Intelligent Systems	1	9.09	67	67.00	2019.0
9	The Hong Kong Polytechnic University	1	9.09	40	40.00	2020.0
10	Shenzhen Institute of Artificial Intelligence and Robotics Society	1	9.09	10	10.00	2021.0

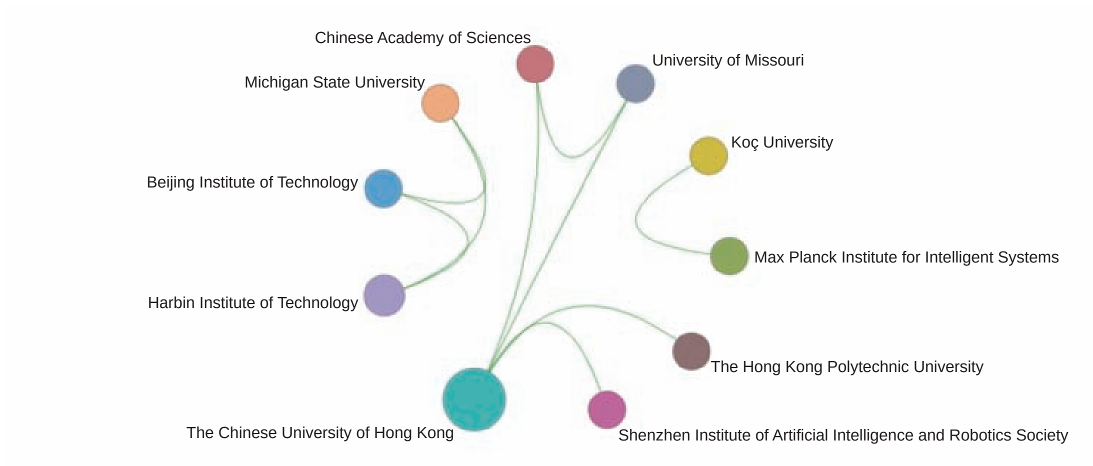

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "dynamically reconfigurable mobile micro-robot swarms"

Table 1.2.11 Countries with the greatest output of citing papers on "dynamically reconfigurable mobile micro-robot swarms"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	323	51.52	2020.8
2	USA	90	14.35	2020.8
3	Germany	42	6.70	2020.5
4	Republic of Korea	41	6.54	2020.8
5	Switzerland	24	3.83	2021.0
6	Japan	20	3.19	2021.0
7	Canada	19	3.03	2020.9
8	Italy	19	3.03	2020.7
9	UK	19	3.03	2020.7
10	Netherlands	15	2.39	2020.9

Table 1.2.12 Institutions with the greatest output of citing papers on “dynamically reconfigurable mobile micro-robot swarms”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	The Chinese University of Hong Kong	102	32.28	2020.5
2	Chinese Academy of Sciences	47	14.87	2020.8
3	Harbin Institute of Technology	40	12.66	2021.0
4	Swiss Federal Institute of Technology	21	6.65	2021.1
5	Max Planck Institute for Intelligent Systems	20	6.33	2020.4
6	Tsinghua University	17	5.38	2020.9
7	Shenzhen Institute of Artificial Intelligence and Robotics Society	15	4.75	2021.1
8	City University of Hong Kong	14	4.43	2021.1
9	Beihang University	14	4.43	2021.1
10	Beijing Institute of Technology	13	4.11	2020.9

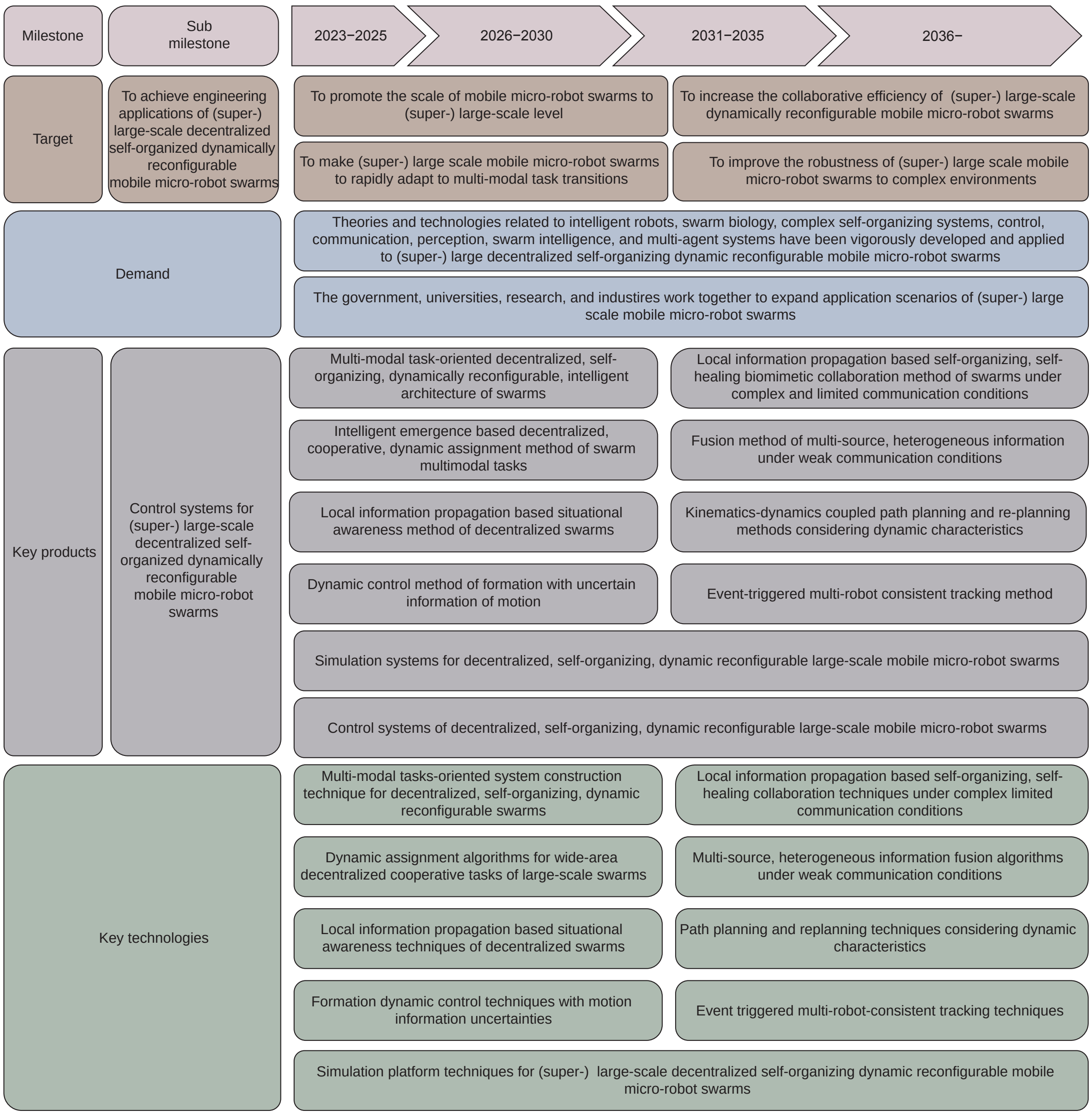

Figure 1.2.9 Roadmap of the engineering research front of “dynamically reconfigurable mobile micro-robot swarms”

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

Top ten development (as opposed to research) fronts in mechanical and vehicle engineering are listed in Table 2.1.1. Some of these fronts are characterized by in-depth traditional research: "multi-robot collaborative operation optimization technology", "unmanned aerial vehicle path planning technology", "precision guidance technology for MUAV"[1], "AI-based precise target recognition", "multi-functional high-performance aerospace composites technology", "micro high-performance combinational sensing technology", and "control and perception system of intelligent mobile robot". There are also other fronts that are newly emerging: "low-cost reusable spacecraft", "underwater unmanned rescue vehicle", "energy integration and propellant management technology for space transportation systems". Table 2.1.2 shows the annual number of core patents published from

Table 2.1.1 Top 10 engineering development fronts in mechanical and vehicle engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Multi-robot collaborative operation optimization technology	465	1 943	4.18	2020.4
2	Low-cost reusable spacecraft	142	612	4.31	2019.9
3	Underwater unmanned rescue vehicle	185	512	2.77	2020.0
4	Unmanned aerial vehicle path planning technology	911	6 525	7.16	2020.5
5	Precision guidance technology for MUAV	483	1 932	4.00	2019.9
6	AI-based precise target recognition	615	1 340	2.18	2021.1
7	Multi-functional high-performance aerospace composites technology	1 102	5 777	5.24	2019.8
8	Energy integration and propellant management technology for space transportation systems	363	2 135	5.88	2019.8
9	Micro high-performance combinational sensing technology	205	245	1.20	2019.6
10	Control and perception system of intelligent mobile robot	569	6 729	11.83	2019.8

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in mechanical and vehicle engineering

NO.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Multi-robot collaborative operation optimization technology	32	35	52	78	126	142
2	Low-cost reusable spacecraft	18	18	21	24	30	31
3	Underwater unmanned rescue vehicle	11	25	39	34	32	44
4	Unmanned aerial vehicle path planning technology	52	75	108	157	203	316
5	Precision guidance technology for MUAV	46	73	79	89	93	103
6	AI-based precise target recognition	4	14	39	112	168	278
7	Multi-functional high-performance aerospace composites technology	177	148	147	163	211	256
8	Energy integration and propellant management technology for space transportation systems	39	65	44	64	87	64
9	Micro high-performance combinational sensing technology	35	32	31	28	38	41
10	Control and perception system of intelligent mobile robot	58	93	82	119	108	109

1 MUAV: miniature unmanned aerial vehicle.

2017 to 2022. "Multi-robot collaborative operation optimization technology", "unmanned aerial vehicle path planning technology", and "AI-based precise target recognition" are the most significant directions of patent disclosure in recent years.

(1) Multi-robot collaborative operation optimization technology

Multi-robot collaborative operation optimization technology refers to a technique that enhances overall efficiency and performance by coordinating the actions and decisions of multiple robots within a given task or work scenario. This technology is primarily applied in the fields of manufacturing, warehousing logistics, surveillance and reconnaissance, environmental sensing, and emergency search and rescue. It also covers several aspects, such as communication, cooperation, planning, and decision-making among multiple robots. Research in this area mainly focus on three aspects: ① cooperative transmission computing, wherein multiple robots share and transmit computing resources to enhance overall computational capabilities; ② distributed sensing, wherein multiple robots simultaneously engage in data collection and measurement within a work scenario to obtain accurate information about the environment or task status; and ③ cooperative control, which involves the development of control strategies and methods enabling multiple robots to cooperate and work together towards achieving common goals. In the future, multi-robot collaborative operation optimization technology is expected to evolve toward intelligence, cross-domain applications, multimodal sensing, human–machine collaboration, and learning. This development will promote the extensive utilization of robot systems across various domains, thus facilitating more efficient, secure, and intelligent cooperative operations.

(2) Low-cost reusable spacecraft

Given the increasing frequency of human space exploration and development activities, the current single-use spacecraft cannot easily meet the demand because of the high-cost and long preparation cycle. Therefore, reusable spacecraft, which can adapt to convenient and low-cost exploration, development, and utilization of space resources, has been receiving increasing attention. Reusable spacecraft is an advanced spacecraft application model that can effectively prolong the life, reduce the operation cost, and improve the reliability and convenience of spacecraft. All major space powers have taken reusable spacecraft as the key breakthrough direction for the sustainable development of space technology. Reusable manned spacecraft and cargo spacecraft, space shuttles, and reusable orbital maneuvering vehicles are typical reusable spacecraft. Reusable spacecraft is not a new concept, but it is extremely difficult to develop because of its huge difference from the traditional single-use spacecraft in design concepts and methods, posing a great challenge to the human science and technology development level. Recently, the key research directions in reusable spacecraft have included reusable design theory and method, reusable spacecraft integrated design, reliable and accurate return and landing technology, long-term on-orbit precise orbit/attitude/thermal control and maintenance technology, highly reliable and reusable high-temperature and ablative resistance thermal protection technology, structure life assessment, and health management technology.

(3) Underwater unmanned rescue vehicle

Underwater unmanned rescue vehicle (UURV) refers to a type of underwater vehicle equipped with underwater detection equipment and operation devices to perform emergency rescue tasks in the water. At present, typical UURVs are mainly developed from remotely operated vehicles (ROV). Compared with traditional underwater vehicles, the working environment of UURV is quite complicated and changeable, especially given the higher time requirements of task execution. To cope with the variety of rescue tasks, the configuration, operation mode, and control strategy of ROVs need to be optimized and upgraded.

At present, the main research highlights in this field include functional structure optimization of UURVs, multisource data fusion processing based on acoustic-optic sensors, integrated high-precision navigation and localization technology, and nonlinear model predictive control for the pose of UURVs. The multi-mode autonomous and remote UURV will be the future development trend in this field. It combines the advantages of remotely operated ROVs in local areas with the advantages of autonomous underwater vehicles (AUVs) that can navigate autonomously over a wide area. Specifically, the technology development trend includes the optimized design of variable configuration functional structure based on the bionic structure, the autonomous detection and recognition technology of underwater rescue targets based on multisource sensor data, and the autonomous decision technology of target rescue based on deep learning.

(4) Unmanned aerial vehicle path planning technology

Unmanned aerial vehicle (UAV) path planning technology aims to autonomously propose a secure and smooth trajectory from the starting point to the target by comprehensively considering task, environmental, and UAV dynamic constraints. Traditionally, path planning algorithms are commonly based on sampling, numerical optimization, and heuristic search methods, such as A*, rapid-exploration random tree, artificial potential field, dynamic programming, Bézier curve, genetic, and particle swarm optimization algorithms. Nevertheless, with the tremendous progresses in the maneuverability of UAVs and the increasingly severe and complex operating environments, the aforementioned routine algorithms face challenges in effectively addressing the requirements of real-time responsiveness, smoothness and security. Additionally, the existing methods are apt to fall into local optima, thus rendering the final destination unreachable. With the development of artificial intelligence (AI) technology represented by deep reinforcement learning, path planning using both Q-network and deep deterministic policy gradient has become a critical research topic. The merit of such a kind of algorithms lies in the elimination of prior knowledge and allowing for direct iterative training. They optimize decisions merely according to environmental feedback information, demonstrating superb generality and transferability. However, it is still arduous to design the reward function and to tune the parameters so as to guarantee convergence of the iterative learning procedures. Therefore, an inevitable tendency in this research field is to design fusion path planning algorithms that combine the virtues of traditional and novel AI-inspired algorithms. More precisely, through using traditional heuristic search algorithms for real-time planning of optimal paths and simultaneously integrating deep reinforcement learning algorithms to achieve autonomous collision avoidance in complex environments, it becomes tractable to break through the technical bottlenecks of both kinds of methods. Furthermore, lightweight path planning techniques, such as the dimensional reduction of UAV parameter space and high-quality modeling of feasible regions, have also received increasing research attentions. In recent years, given its unique self-attention mechanism, a promising Transformer architecture has been used in auto drive systems such as environmental perception and segmentation, target detection, tracking and positioning, path planning and decision-making modules. Accordingly, the Transformer architecture can be expected to become a new path planning paradigm for unmanned aerial vehicles.

(5) Precision guidance technology for MUAV

A miniature unmanned aerial vehicle (MUAV) is generally considered as a type of unmanned aerial vehicle (UAV) that is characterized by a typical size ranging from several centimeters to tens of centimeters and a maximum take-off weight ranging from several grams to dozens of kilograms. In addition, it typically possesses the following features: small volume, light weight, and super maneuverability. MUAV precision guidance technology refers to the use of MUAV as the application carrier for controlling guidance weapons and accurately hitting the target in a complex battlefield environment. The realization of MUAV precision guidance relies on the functions provided by MUAV, including target identification and tracking with characteristics from the target (e.g., reflection, scattering, and radiation), and the navigation information of the MUAV that leverages inertial and information support technologies. In a complex environment with terrain constraints, precision guidance technology can effectively improve the guidance accuracy of MUAVs, reduce the risk of accidental injuries, and expand war results, which are significant for anti-terrorism actions and military attacks. At present, research on MUAV precision guidance technology focuses on the fields of precision detection, comprehensive utilization of information support, and high-precision guidance control. As the emergence of novel models of manned/unmanned collaborative combat imposes the requirements of high stealth in air confrontation, high density in cluster confrontation, and high intelligence in attack–defense confrontation, the development direction of MUAVs in the future includes the following fields: ① compound guidance technology that improves the hit accuracy of MUAVs, ② intelligent recognition and cluster algorithm that improve the ability of collaborative combat in intelligent combat scenes, and ③ novel microstructure and materials that improve the stealth penetration ability of MUAVs.

(6) AI-based precise target recognition

The precise target recognition technology based on AI refers to utilizing the powerful learning and fitting capabilities of machine learning and pattern recognition to achieve accurate analysis of scene semantic information, including environmental perception, target extraction, segmentation, and tracking. It is often based on single sensors or their combinations, such as cameras, infrared EDM instruments, LIDAR, navigation radars, and millimeter wave radars, as information sources. In recent application scenes, the abruptly increasing complexities include abundant scene information, multiple target overlaps, and pose diversities, which are accompanied by severe limitations, such as occlusion, viewpoint distortion, sparkling lights, rains, fogs, vibrations, and other conditions. These adverse factors inevitably constrain the comprehensiveness and precision improvement of modern recognition systems. For example, unmanned surface vehicles (USVs) often face sudden marine accidents. The challenge lies in rapidly and accurately capturing and tracking tasks of emergent targets, which could not be fulfilled by traditional recognition algorithms. As a result, researchers turn to seek assistance from the superb feature extraction and spatial mapping capabilities of AI, with deep learning as a representative, to address the performance degradation problem caused by the abovementioned severe limitations. In previous years, such a promising Transformer architecture has been revolutionarily introduced into the field of target recognition. Its unique self-attention mechanism allows adaptively establishing multilevel, cross-space, and cross-temporal correlations in information, significantly improving recognition accuracy. Transformer architecture has replaced convolutions of deep learning and thus becomes a mainstream framework for new generation target recognition systems. Recently, the emergence of large language models has also shed new insights into target recognition. Researchers have begun to explore large models in the specified field of target recognition, which is no longer confined to specific tasks or scenarios. In brief, AI is the essential driving force for achieving precise target recognition. Current research focuses on various missions, including the application of instance segmentation based on the Transformer framework, the development of universal large models for target recognition scenarios, the construction of panoramic semantic recognition systems in complex environments, and the advancement of spatiotemporal alignment and fusion algorithms for multisource information. Transformer has even become a new environment perception paradigm for auto driving, which has profoundly changed the modern human life. In the future, in consideration of the increasing complexity of application scenes, new advanced AI technology will be developed to fulfill the upgrading mission for environmental perception and situational awareness.

(7) Multi-functional high-performance aerospace composites technology

Multi-functional composites offer not only excellent mechanical properties for aerospace vehicles but also bestow them with a range of functional properties, including wave-absorption, wave-transmission, thermal protection, conductivity, electromagnetic shielding, vibration reduction, and energy absorption. Moreover, the next generation of aerospace equipment designed and manufactured using these multi-functional composites demonstrates remarkable adaptability to complex flight environments, encompassing air, space, land, and sea integration, even in the face of drastic changes in temperature, humidity, and salinity. Consequently, this disruptive technology has garnered significant attention from major aerospace powers worldwide. The current research in high-performance multi-functional aerospace composite technology primarily centers around various aspects, including multi-scale and multi-physics analysis theory and modeling methods, the absorption mechanism of radar/infrared multi-spectrum composites, integrated design and additive manufacturing of function-material-structure composite systems, repairing mechanisms and manufacturing methods for self-diagnosing/self-repairing composites, and high-performance assembly techniques for multi-functional composite structures. Looking ahead, the development of high-performance multi-functional composites is anticipated to achieve breakthroughs in the following directions: ① leveraging machine learning approaches for multi-physics performance modeling and design methods of multi-functional composites; ② developing intelligent sensor-control-actuation integrated composite systems derived from environmentally sensitive materials; and ③ exploring high-performance and cost-effective natural materials for manufacturing lightweight, high-strength, and environmentally friendly multi-functional composites.

(8) Energy integration and propellant management technology for space transportation systems

The energy integration and propellant management technology for space shuttle transportation systems is a general term for a class of technologies that integrate and optimize multiple energy systems in space vehicles that travel between the Earth's surface and orbit, and manage propellants safely and efficiently. Energy integration refers to the comprehensive consideration of the four links of energy supply, transmission and storage, terminal consumption and recovery, and the adoption of interrelated technologies and management measures in each link to achieve system optimization in the entire energy system as a whole. In-situ energy technology and equipment use extraterrestrial water ice resources and space hydrogen energy power integration technology for the precise matching, regulation, and efficient utilization of energy consumption in the space-to-space round-trip process, energy storage, distribution, dynamic organization, and production of energy. The main research direction of system energy integration is accurate prediction technology. Moreover, the main research directions of propellant management technology are the long-term on-orbit position management and heat management technology of cryogenic propellant, the space on-orbit cross-transfer technology of cryogenic propellant, and the modeling and simulation technology of the integrated fluid management (IVF) system. With the ever-increasing requirements for round-trip transport between the Earth and low Earth orbit, heavy-duty launch vehicles built with large-thrust engines and large-diameter structure technologies, new power, high-precision return control, and other technologies are used to develop reusable vehicles. In addition, energy integration and low-temperature propellant long-term technologies, such as on-orbit management, are receiving increasing attention.

(9) Micro high-performance combinational sensing technology

As the only functional device for information acquisition and data collection, sensing technology is one of the core technologies in the era of digital economy and one of the cornerstones of intelligent manufacturing and information technology. At present, robots, smart manufacturing, smart transportation, smart cities, and wearable technology are developing rapidly, requiring sensing technology to develop in the direction of miniaturization, high performance, low power consumption, intelligence, integration, and low cost. Micro high-performance combinational sensing technology integrates various miniature high-performance sensing functions to achieve accurate measurement of multiple-type and/or multi-dimensional physical signals on a small chip. Combinational sensing technology can be realized by micro-machining technology through the integration of multi-functional micro-sensing chips with different functions. This technology has the characteristics of high integration level, small size, and mutual compensation and correction between different sensing functions, which allow highly accurate data acquisition with great completeness. With the rapid development of micro-nano manufacturing, multi-functional composite, precision packaging, and digital compensation technologies, new sensing principles, materials, and processes are constantly emerging, enabling the development of new types of sensing elements with new principles and effects. This development trend also continuously promotes the integration of more sensor units/functions, which has become the main research hotspot and development direction of the current miniature high-performance compound sensor technology.

(10) Control and perception systems of intelligent mobile robots

Control and perception systems are crucial for intelligent mobile robots to achieve environmental awareness, dynamic decision making and planning, and behavior execution. These systems primarily consist of sensory modules and computation and decision-making modules. For successful navigation in unknown or dynamic environments, robots need to have accurate perception of their surroundings. This perceptual information is further used for the robot's decision making and action execution. As mobile robots find widespread applications, the demand for their intelligence grows. Deep learning and perception, simultaneous localization and mapping (SLAM), reinforcement learning and control, multi-modal perception and sensor fusion, human–robot interaction and collaboration, robotic swarm coordination, edge computing and perception, and bio-inspired methods are currently the major research hotspots in this field. Considering the uncertainty and dynamism of real-world environments, ensuring that robots maintain stable and effective operations in complex and changing settings is a significant research direction. As robots become more prevalent in public spaces and homes, concerns about their operational safety and ethical issues are increasingly gaining attention.

2.2 Interpretations for three key engineering development fronts

2.2.1 Multi-robot collaborative operation optimization technology

Multi-robot collaborative operation optimization technology refers to the methodologies and techniques employed to enhance overall work efficiency and performance in scenarios involving the use of multiple robots. The primary objective of this technology is to facilitate effective coordination and cooperation among robots through efficient task planning, resource allocation, decision-making, and coordination mechanisms, among others. Furthermore, this kind of optimization technology aims to enable multiple robots to collaborate more efficiently and accomplish complex tasks together through the application of rational algorithms and strategies. This technology finds its principal applications within various sectors, including manufacturing, warehousing logistics, surveillance and reconnaissance, environmental sensing, and emergency search and rescue. It also encompasses various aspects involving communication, cooperation, planning, and decision-making among multiple robots.

Multi-robot collaborative operation is a multidisciplinary cross-cutting technology at the scientific frontier. It combines interdisciplinary frontier technologies and covers categories, such as game theory and operations research in artificial intelligence. It is also closely related to numerous disciplines, such as complex systems, information theory, and control theory. Thus, it is also recognized as an international challenge. In particular, the optimization of multi-robot collaborative operation urgently needs to address three scientific and technological challenges. The first set of challenges deals with the integration of efficient transmission–computation collaborative mechanisms for multiple robots. This involves research on low-latency, high-reliability communication network theory for multi-robot collaborative operation in complex tasks, efficient cross-layer heterogeneous data communication and sharing methods, as well as the establishment of an integrated communication network for multi-robot collaborative operation to guarantee high real-time and reliable information transmission and computation.

The second set of challenges deals with mechanisms for large-scale precise perception and distributed feature recognition. It involves exploring quantitative descriptions and coupled transmission mechanisms of temporal–spatial perception errors of multiple robots; clarifying the mechanisms of large-scale autonomous collaborative measurement and information fusion of heterogeneous sensors; establishing task-driven multiscale, multi-objective identification general models, and continuous cognitive learning architectures for complex tasks; and forming multi-robot embodied perception and embodied intelligence for complex tasks.

The final set of challenges deals with perception–cognition–decision–control collaborative operation mechanism. In particular, it involves building system models that integrate task data and mechanistic knowledge; establishing safe, efficient, robust, and scalable task scheduling and dynamic programming systems to ensure orderly operation of large-scale complex tasks; establishing mechanisms for multi-robot autonomous decision-making to adapt to the strong time-varying dynamic interaction demands between multiple robots and complex environments; constructing a multi-process full-link collaborative operation model; exploring self-optimization mechanisms for parameters of multi-robot collaborative operation systems; and finally, improving the accuracy, stability, and safety of multi-robot system operations.

In summary, the optimization technology for multi-robot collaborative operation can improve production efficiency and product quality, reduce operation costs, and minimize personnel risks. Therefore, it has broad application prospects in the fields of industrial production, agriculture, logistics, healthcare, and others. Furthermore, it is one of the important underlying technologies that can help promote intelligent manufacturing and smart societies.

Currently, the country with the largest number of core patents published in this field is China, and the top country with the highest average citations per paper is Republic of Korea, as shown in Table 2.2.1. Cooperation can be observed between India, Peru, and Malaysia. And cooperation can also be observed between India and Sweden, as shown in Figure 2.2.1. The top three institutions with the largest number of core patents are Beijing Institute of Technology, Guangzhou Institute of Advanced Technology, Chinese Academy of Sciences, and 3MTOP Company Limited, respectively, as shown in Table 2.2.2. No cooperation can be observed between the institutions with core patent disclosures. Figure 2.2.2 shows the roadmap of the engineering development front of "multi-robot collaborative operation optimization technology".

Table 2.2.1 Countries with the greatest output of core patents on “multi-robot collaborative operation optimization technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	416	89.46	1 518	78.13	3.65
2	USA	26	5.59	207	10.65	7.96
3	Republic of Korea	14	3.01	197	10.14	14.07
4	India	6	1.29	9	0.46	1.50
5	Colombia	2	0.43	12	0.62	6.00
6	Switzerland	1	0.22	0	0.00	0.00
7	Malaysia	1	0.22	0	0.00	0.00
8	Peru	1	0.22	0	0.00	0.00
9	Sweden	1	0.22	0	0.00	0.00

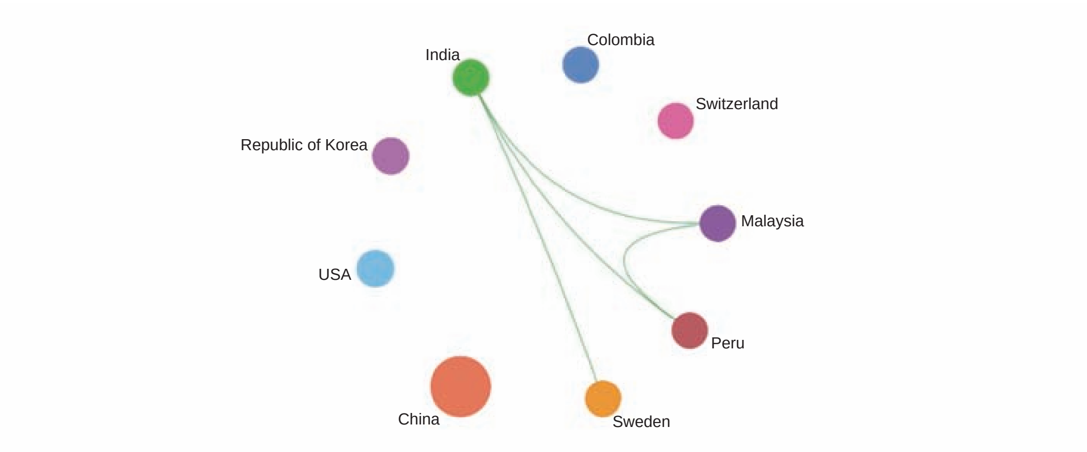

Figure 2.2.1 Collaboration network among major countries in the engineering development front of “multi-robot collaborative operation optimization technology”

Table 2.2.2 Institutions with the greatest output of core patents on “multi-robot collaborative operation optimization technology”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations	Citations per patent
1	Beijing Institute of Technology	19	4.09	46	2.37	2.42
2	Guangzhou Institute of Advanced Technology, Chinese Academy of Sciences	12	2.58	44	2.26	3.67
3	3MTOP Company Limited	12	2.58	3	0.15	0.25
4	The Boeing Company	11	2.37	66	3.40	6.00
5	Hunan University	10	2.15	21	1.08	2.10
6	Nanjing University of Aeronautics and Astronautics	10	2.15	7	0.36	0.70
7	Southeast University	9	1.94	107	5.51	11.89
8	Harbin Institute of Technology	8	1.72	91	4.68	11.38
9	Xidian University	8	1.72	42	2.16	5.25
10	Harbin Engineering University	8	1.72	34	1.75	4.25

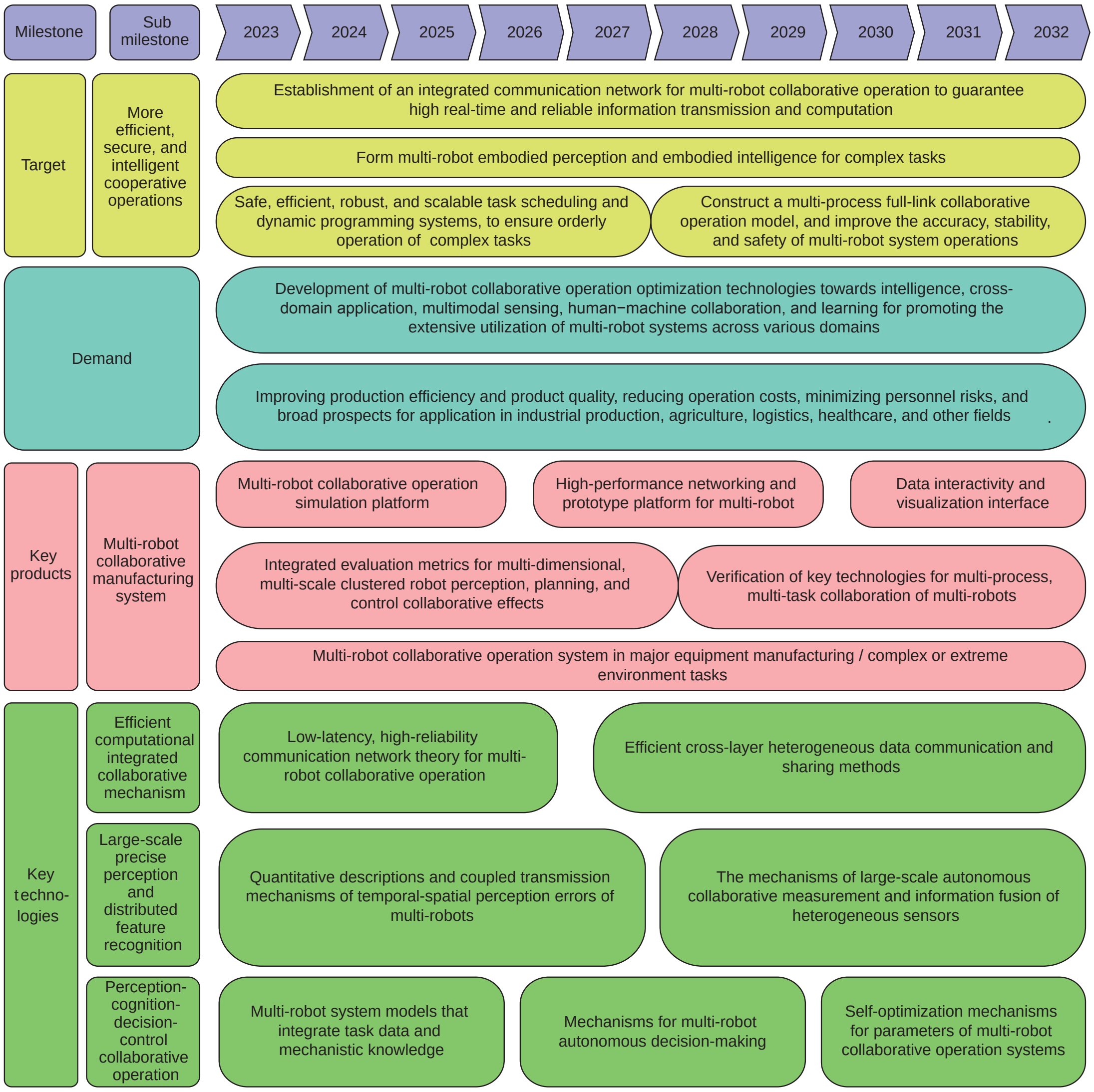

Figure 2.2.2 Roadmap of the engineering development front of “multi-robot collaborative operation optimization technology”

2.2.2 Low-cost reusable spacecraft

With the continuous expansion of space activities and the steady increase in launch frequency, the high cost of traditional expendable spacecraft has become a key factor restricting the development of space exploration. To overcome this challenge, reusable technology is considered one of the main approaches to reducing operational costs and enhancing the sustainability of space technology. In recent years, various spacefaring nations have actively explored the development of reusable spacecraft and proposed corresponding development roadmaps, achieving significant accomplishments in this field. Notable examples include USA’s SpaceX Dragon spacecraft and Boeing CST-100, China’s Shenzhou spacecraft, Russia’s Soyuz MS spacecraft, and Blue Origin’s New Shepard suborbital spacecraft. These spacecrafts emphasize the concept of reusability, making breakthroughs in design principles and methodologies, such as streamlined structures, autonomous control, vertical landings, and optimized materials. Consequently, they have successfully undergone recovery and reuse after completing their missions.

In the future, reusable space vehicles will primarily be applied to near-earth orbital missions and interplanetary transport missions. Compared with traditional disposable space vehicles, these spacecrafts undergo significant paradigm shifts in design concepts and methodologies. Currently, the focus of reusable technology remains on component-level reuse, where certain functional units undergo reusability assessments and continue to serve their original purposes after direct or minor repairs on new space vehicles. However, achieving spacecraft-level reusability still presents challenges. Therefore, considering the developmental trajectories of leading spacefaring nations, the advancement of reusable space vehicles across different mission levels requires concentrated breakthroughs in a set of common key technologies.

The primary focus lies in the key technology of overall design, where it is essential to establish a technical theoretical system for reusable space vehicles. This task involves optimizing and demonstrating the overall scheme from aspects such as technical risks, reliability, safety, and economic benefits. Specific areas of research encompass mission planning, overall layout, health management, system and subsystem reliability modeling and assessment, and experimental verification. Next, the hardware components critical for achieving spacecraft reusability consist of the propulsion system, the shock-resistant structure, lightweight ablative materials, and precise non-destructive landing and recovery technology. The development of the propulsion system will address degradation reduction, the thermal protection of combustion chambers, and power adjustment techniques. Advancements in structures and materials will focus on efficient load-bearing, integrated and sealed structures, and lightweight ablative materials. For precise non-destructive landing, challenges such as coordinating multiple engines for retro-thrust deceleration, vector control, non-destructive testing, and designing reusable buffers with anti-fatigue and durability properties must be overcome. Furthermore, intelligent measurement and automation decision control technology will be of utmost importance during mission execution because it will determine the precision of orbital maneuver control and re-entry guidance, ensuring compliance with environmental adaptability requirements throughout the entire lifecycle.

The countries with the largest number of core patents published in this field are China, USA, and Russia; the top country with the highest citations per paper is France, as shown in Table 2.2.3. No cooperation can be observed between the countries with core patents. The top two institutions with the highest number of patents are Aerospace Research Institute of Special Materials and Processing Technology and Boeing Company, as shown in Table 2.2.4. Cooperation can be observed between Johann Haltermann Limited and Monument Chemical Houston Limited Liability Company, as shown in Figure 2.2.3. Figure 2.2.4 shows the roadmap of the engineering development front of “low-cost reusable spacecraft”.

Table 2.2.3 Countries with the greatest output of core patents in the engineering development front of “low-cost reusable spacecraft”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	72	50.70	327	53.43	4.54
2	USA	30	21.13	81	13.24	2.70
3	Russia	14	9.86	7	1.14	0.50
4	France	12	8.45	170	27.78	14.17
5	Spain	6	4.23	23	3.76	3.83
6	Germany	4	2.82	0	0.00	0.00
7	Colombia	2	1.41	0	0.00	0.00
8	India	1	0.70	0	0.00	0.00

Table 2.2.4 Institutions with the greatest output of core patents in the engineering development front of "low-cost reusable spacecraft"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Aerospace Research Institute of Special Materials and Processing Technology	24	16.90	170	27.78	7.08
2	Boeing Company	11	7.75	4	0.65	0.36
3	European Aeronautic Defence and Space Company	8	5.63	160	26.14	20.00
4	Johann Haltermann Limited	8	5.63	0	0.00	0.00
5	Monument Chemical Houston Limited Liability Company	8	5.63	0	0.00	0.00
6	Pangea Aerospace	7	4.93	27	4.41	3.86
7	Beijing Xingji Rongyao Space Technology Company Limited	5	3.52	35	5.72	7.00
8	Beijing Space Vehicle General Design Department	5	3.52	4	0.65	0.80
9	Nanjing University of Aeronautics and Astronautics	4	2.82	26	4.25	6.50
10	ArianeGroup SAS	4	2.82	10	1.63	2.50

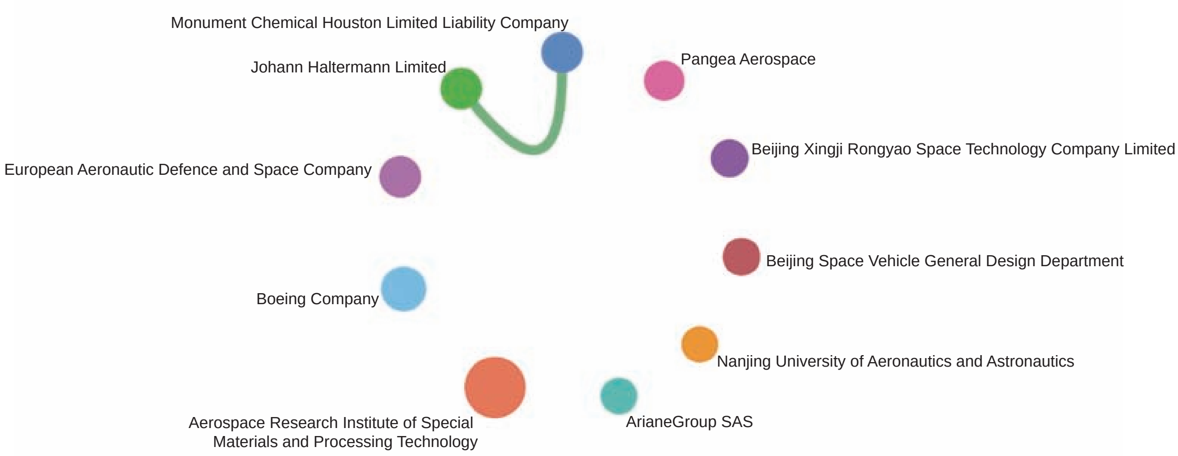

Figure 2.2.3 Collaboration network among major institutions in the engineering development front of "low-cost reusable spacecraft"

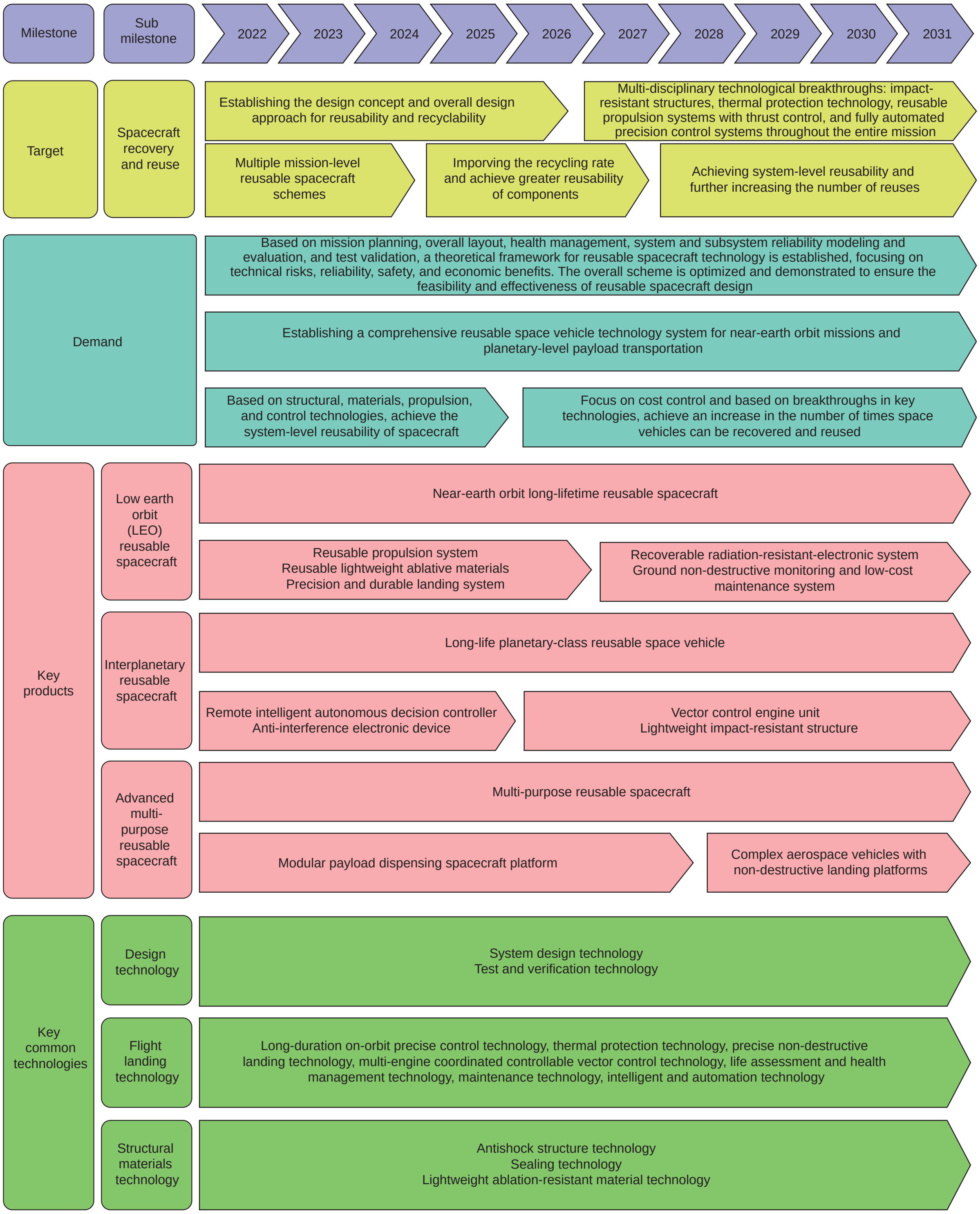

Figure 2.2.4 Roadmap of the engineering development front of “low-cost reusable spacecraft”

2.2.3 Underwater unmanned rescue vehicle

With the growth of human activities such as offshore trade, marine surveys, and marine resources exploitation, the occurrence of accidents in the ocean has increased in frequency. These accidents have caused great losses to the economic development of the country. Utilizing advanced emergency rescue equipment to carry out rescue activities is of great significance in improving the effectiveness of rescue missions, reducing losses in accidents, and saving lives. As the complexity and variability of the underwater operating environment, the executive efficiency and actual effect of underwater emergency rescue missions are not as expected. Underwater unmanned rescue vehicles (UURVs) have progressively played a major role in the underwater emergency rescue equipment system owing to their advantages of strong operational capability and high autonomy. From the 1970s when the first UURV appeared to the present, with the development of sensors and intelligent control technology, the autonomy and operational capabilities of UURVS have been remarkably improved. Their roles in underwater emergency rescue missions have become vital.

To cope with diversified rescue demands and strict environments, the intelligent control strategy, environment perception, and self-learning of UURVs have become the current research hot topics in underwater robotics. The research on UURVs in China started relatively later but has been developing rapidly in recent years. The related research is mainly in three aspects. First is the structural aspect, particularly the application of new types of mechanisms, new materials, and new drives to the mechanism design of UURVs. The optimized design of bionic-structure-based variable configuration functional structure, multi-mode function fusion, and reconfigurable modular design are the development trends in this aspect. Second is the environmental adaptability aspect. Through multi-sensor fusion technology, high-efficiency information acquisition and processing technology, and multi-task parallelism dynamic analysis, accurate environmental sensing in the complex marine environment is realized. Multi-source data fusion processing technology based on acoustic and optical sensors and multi-source sensor data-based target detection and recognition technology are the development trends in this aspect. Third is the intelligent development aspect. Through related technologies such as dynamic probabilistic network decision-making methods and reinforcement learning methods, efficient autonomous decision-making control under complex tasks is achieved. The nonlinear model predictive control for the pose and the autonomous decision technology of target rescue based on deep learning are the trends in this aspect. In conclusion, UURV technology has important research value in control engineering, sensors, artificial intelligence, and other multidisciplinary fields. Exploring it also has great practical meaning for guaranteeing the safety of maritime activities and improving the level of underwater emergency rescue in China.

The country with the largest number of core patents published in this field is China, and the top country with the highest citations per paper is USA, as shown in Table 2.2.5. No cooperation can be observed between the countries with core patents. The top institution with the highest number of patent is Yuhong (Nanjing) Technology Company Limited, as shown in Table 2.2.6. Cooperation can be observed between Beibu Gulf University, Guangzhou Shunhai Shipbuilding Company Limited, and South China University of Technology, as shown in Figure 2.2.5. Figure 2.2.6 shows the roadmap of the engineering development front of “underwater unmanned rescue vehicle”.

Table 2.2.5 Countries with the greatest output of core patents in the engineering development front of “underwater unmanned rescue vehicle”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	178	96.22	454	88.67	2.55
2	USA	2	1.08	58	11.33	29.00
3	Republic of Korea	2	1.08	0	0.00	0.00
4	Poland	1	0.54	0	0.00	0.00
5	Russia	1	0.54	0	0.00	0.00
6	Turkey	1	0.54	0	0.00	0.00

Table 2.2.6 Institutions with the greatest output of core patents in the engineering development front of "underwater unmanned rescue vehicle"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Yuhong (Nanjing) Technology Company Limited	5	2.70	0	0.00	0.00
2	Wenzhou Yinuoweite Technology Company Limited	4	2.16	16	3.12	4.00
3	Jiangsu University of Science and Technology	4	2.16	15	2.93	3.75
4	Shenzhen Gaodu Innovation Technology Company Limited	4	2.16	12	2.34	3.00
5	Zhejiang Chuangzhiguo Enterprise Management Consulting Company Limited	4	2.16	8	1.56	2.00
6	Bestway Marine & Energy Technology Company Limited	3	1.62	25	4.88	8.33
7	Guilin University of Electronic Technology	3	1.62	17	3.32	5.67
8	Beibu Gulf University	3	1.62	13	2.54	4.33
9	Guangzhou Shunhai Shipbuilding Company Limited	3	1.62	13	2.54	4.33
10	South China University of Technology	3	1.62	13	2.54	4.33

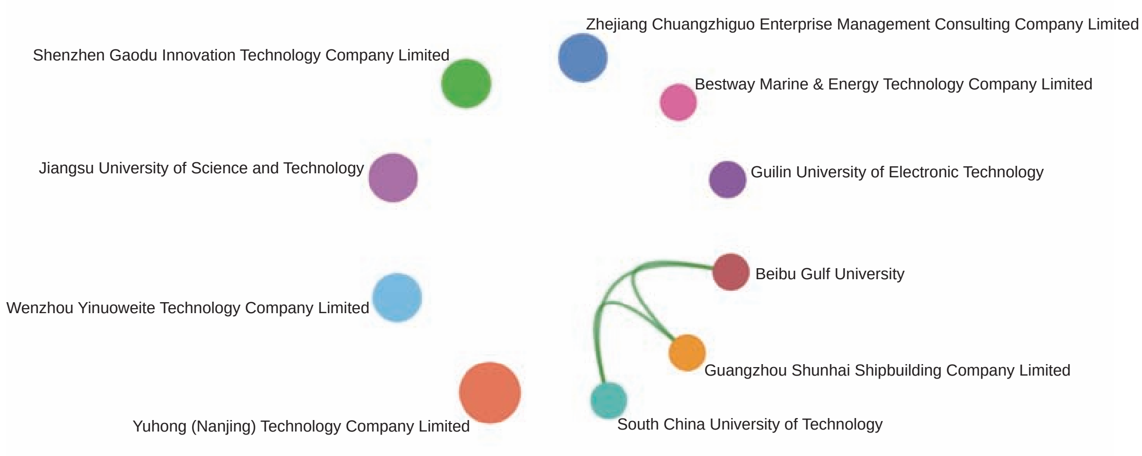

Figure 2.2.5 Collaboration network among major institutions in the engineering development front of "underwater unmanned rescue vehicle"

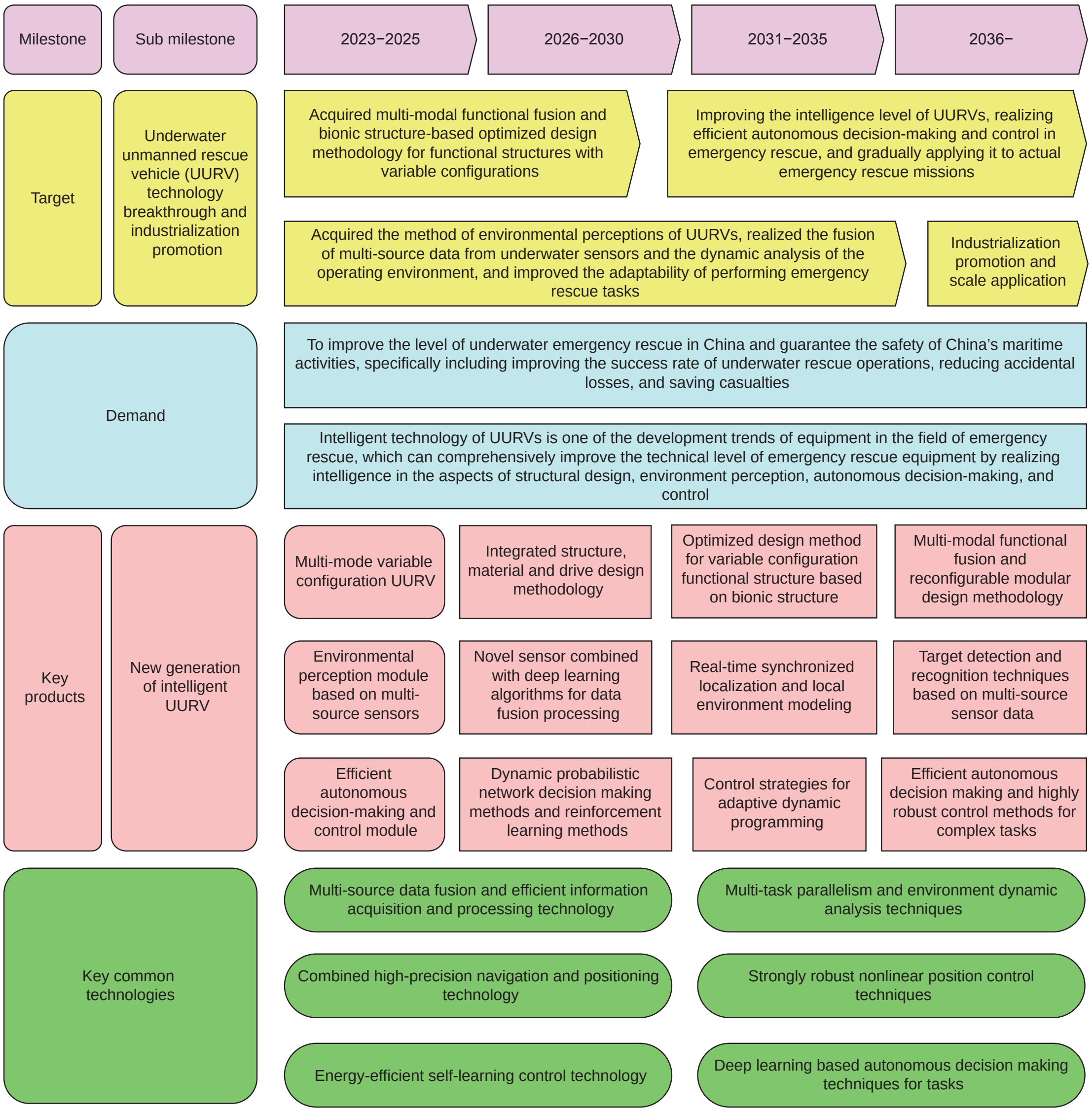

Figure 2.2.6 Roadmap of the engineering development front of "underwater unmanned rescue vehicle"

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II. Information and Electronic Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

Table 1.1.1 summarizes the Top 10 engineering research fronts in the information and electronic engineering field, 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. "Optoelectronic in-sensor computing devices and their integration" is the front of data mining. "Networking theories and key technologies of satellite internet", "ultra-large-scale silicon-based quantum chips", "automatic development of software assisted by artificial intelligence", "systematized gaming and intelligent control for multiagent systems", "cyber-physical security of industrial control systems", and "chip-based satellite laser communication terminal" are fronts of expert nomination. The remaining fronts are data mining & expert nomination. Table 1.1.2 shows the number of core papers published from 2017 to 2022 related to each research front.

(1) Theory and technology of large models and their computing systems

Theory and technology of large models and their computing systems refer to the semi-supervised/unsupervised basic learning theory of large-scale pretrained models and efficient computing technology composed of parameter fine-tuning, reinforcement learning and other mechanisms, as well as model parallel computing and distributed systems based on this and their optimization strategies and deployment scheme. Large models are pretrained on large-scale data based on learning mechanisms, such as self-supervision, and have powerful representation and generalization capabilities, usually with a large number of parameters. Large models eliminate the dependence on large amounts of labeled data and can serve downstream applications through model fine-tuning, prompt fine-tuning, and context learning for specific tasks. They possess general intelligence capabilities for tasks in multiple application scenarios. Research on the theory and technology of large models and their computing systems is currently maintaining high-speed iterations, and has quickly penetrated applications such as natural language, smart medical care, multimodal generation, and autonomous driving. The theory and technology of large models and their computing systems provide an impetus and theoretical foundation for improving the performance, efficiency, and generalization capabilities of large models. The main research directions include the theoretical framework of large models, large model structures, and training mechanisms,

Table 1.1.1 Top 10 engineering research fronts in information and electronic engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Theory and technology of large models and their computing systems	34	2 231	65.62	2020.2
2	Networking theories and key technologies of satellite internet	31	1 354	43.68	2020.5
3	Ultra-large-scale silicon-based quantum chips	56	6 779	121.05	2019.7
4	Photon-integrated lasers for quantum applications	63	4 188	66.48	2019.5
5	Extra-large-scale and ultra-wideband antenna array communication theory and technologies	19	1 417	74.58	2019.7
6	Optoelectronic in-sensor computing devices and their integration	56	5 417	96.73	2020.8
7	Automatic development of software assisted by artificial intelligence	37	586	15.84	2019.8
8	Systematized gaming and intelligent control for multiagent systems	39	1 636	41.95	2019.8
9	Cyber-physical security of industrial control systems	118	5 816	49.29	2019.9
10	Chip-based satellite laser communication terminal	111	3 047	27.45	2019.6

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in information and electronic engineering

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Theory and technology of large models and their computing systems	4	3	3	6	8	10
2	Networking theories and key technologies of satellite internet	1	2	4	6	9	9
3	Ultra-large-scale silicon-based quantum chips	10	6	8	11	11	10
4	Photon-integrated lasers for quantum applications	10	11	11	11	9	11
5	Extra-large-scale and ultra-wideband antenna array communication theory and technologies	2	3	4	3	3	4
6	Optoelectronic in-sensor computing devices and their integration	2	4	6	6	13	25
7	Automatic development of software assisted by artificial intelligence	5	5	6	6	7	8
8	Systematized gaming and intelligent control for multiagent systems	5	5	5	8	9	7
9	Cyber-physical security of industrial control systems	10	17	22	22	22	25
10	Chip-based satellite laser communication terminal	9	25	22	18	14	23

and distributed training and deployment strategies. The theoretical framework of large models is based on information and over-parameterization theories, and it studies the explanation theory of new characteristics such as emergence and homogeneity while modeling the computational complexity of large models. Research on the structure and training mechanism optimizes the computing system of the unified framework of "pretraining + generalization" for large models, designs more efficient self-supervision mechanisms, and balances the fitting ability and complexity for large models. Distributed training and deployment strategies study the scalability improvement scheme of large models, use methods such as serverless computing to distribute training tasks to multiple computing nodes in the cloud, and use parallel training strategies to overcome the limitations of storage and computing resources. The future development of the theory and technology of large models and their computing systems still needs to address three issues: privacy and security, evaluation methods, and deployment efficiency. First, the training and deployment of large models requires more efficient encryption and secure communication technologies. The development of secure and trustworthy computing solutions is also urgent. Second, automated and general evaluation frameworks are required to benchmark the capability bounds, robustness, and deviation correction capabilities of large models. Additionally, the real-time performance and training energy consumption of large models must be further optimized.

(2) Networking theories and key technologies of satellite internet

Satellite internet is the third internet revolution, after fixed and mobile communication networks. Specifically, satellite internet is a wireless network that is exploited as an access network. On one hand, the satellite internet has overcome the coverage range of the ground internet and realizes seamless global coverage. Even though continents account for only 29% of the global area, only partial urban and rural districts are covered by the ground internet, and efficient wireless coverage is unavailable in remote areas, such as broad oceans, deserts, forests, and mountains. However, the construction of new ground networks in these areas incurs significant costs and maintenance difficulties; therefore, a satellite internet that employs the satellite network as the access network is required. The decrease in the costs of satellite manufacturing, launch, and communication makes it possible to construct the satellite internet of things (IoT) and achieve global coverage through satellite networks. On the other hand, satellite internet has reformed the original network structure, shifting from a people-centered connection to the interconnection of all things. In recent years, with economic and societal development, several wireless devices have been accessed via wireless networks. Satellite internet offers a large access capacity, strong survivability, and low impacts on weather conditions, which can provide interconnection of things in the global range.

Based on the different heights of satellite orbits, satellite networks are usually divided into three categories: low, medium, and high orbit. Low-orbit satellite networks are generally used as access networks for satellite internet because their low-orbit characteristics contribute to low transmission delays and losses. For example, the "Starlink" project of the American company SpaceX employs satellite networks with orbit heights of approximately 500 km. However, low-orbit satellites move quickly and the visible duration of one satellite is short. Therefore, to realize seamless global coverage, several low-orbit satellites must be deployed for networking, i.e., low-orbit satellite constellations. In recent years, both academia and industry have conducted extensive research on networking theories and key technologies for satellite internet, and significant progress has been made, which mainly includes inter-satellite communication technology, satellite network protocols, elastic routing protocols, and mobility management. The introduction of mobile satellite communication without ground stations has further improved the networking forms of the satellite internet and significantly enhanced its functionality. In conclusion, the advantages of satellite internet can be summarized as follows: First, the satellite internet has eliminated dependence on ground devices, greatly enhanced mobility, and truly achieved mobile access in a global range. Second, existing mobile phones can be directly connected to the satellite internet, where downward compatibility can be achieved. In addition, the collaboration of satellite internet and ground networks has enabled the integration of space and earth communication.

(3) Ultra-large-scale silicon-based quantum chips

Quantum computers are expected to surpass classical computers in bringing higher computational power to humanity with quantum chips responsible for computation and information processing at their core. Quantum chips, which tightly integrate quantum circuits onto a substrate, play a vital role in the development of quantum technologies. Unlike the binary chips in classical chips, quantum chips use quantum properties to significantly increase computational parallelism and the ability to handle complex problems. The fabrication of ultra-large-scale quantum chips has become a critical challenge in realizing universal quantum computers because millions of quantum bits (qubits) are required for error correction. Considering that classical computing chips can currently accommodate billions of transistors and that the integrated circuit (IC) industry possesses mature manufacturing techniques and infrastructure, the realization of large-scale silicon-based quantum chips through complementary metal–oxide semiconductor (CMOS) processes holds a natural advantage in terms of scalability and is gradually becoming an international research hotspot in the field of quantum computing.

The development of silicon-based quantum chips involves diverse approaches. One approach involves encoding quantum information onto electron (hole) spins within gate-defined silicon-based quantum dots or phosphorus nuclear spins embedded in silicon. Presently, single-qubit and two-qubit gates have been realized with fidelity that surpasses error-correction thresholds, and the successful construction of quantum processors containing six qubits has been achieved. In the future, the development of silicon-based spin qubits will specifically address the challenges of long-range coupling and uniform high-fidelity in large-scale setups. Additionally, leveraging silicon-based photonic integration processes can facilitate optical quantum computing and communication. Substantial breakthroughs have already been achieved in areas such as high-dimensional quantum entanglement states, quantum key distribution, and quantum teleportation. The evolution of silicon photonics technology requires the compact integration of photon sources, quantum state manipulation, and single-photon detection onto a single chip while minimizing device losses. These advancements have laid the foundation for the quantum computation and communication on silicon-based materials. Consequently, the trajectory of silicon-based quantum chips is set to continue its progression toward large-scale integration and practical applications.

(4) Photon-integrated lasers for quantum applications

Photon-integrated lasers for quantum applications are optical source devices based on technology of planar light waveguide circuit photonic integration and used in fields of quantum optical detection, sensing, measurement, communication and so on. In recent years, in the field of quantum optics, increasing attention has been paid to research on new methods and technologies based on the interaction of lasers and atoms. Specifically, lasers of 509 nm, 633 nm, 780 nm, 795 nm, 852 nm, 976 nm, 1 064 nm, 1 083 nm, 1 310 nm, and 1 550 nm used in optical atomic clocks, Rydberg detection, quantum magnetic probes, gyroscopes, and quantum communication have become mainstream. The traditional quantum light source devices used to generate laser wavelengths are gas, solid, and fiber lasers. Because of their large volume, complex operation, low energy consumption ratio, and lack of reliability, it is difficult to meet the current needs of communication, sensing, and detection in space, air, Earth, sea, and other complex environments. Semiconductor lasers with small size and high efficiency are suitable for these aforementioned applications. Owing to the advantages of direct photoelectric conversion and compatibility with semiconductor processes, they can be used to realize photonic integrated quantum light source devices.

However, because of the size limitations of the resonator and waveguide, semiconductor lasers have high phase noise and poor beam quality, which makes it difficult to meet the requirements of quantum optics for laser spectral purity, wavelength accuracy, and frequency stability. Therefore, it is necessary to use an external optical frequency selection element to induce an internal laser resonator mode through appropriate optical feedback to achieve laser linewidth narrowing, noise suppression, and spectral purification. For a multispectral quantum light source extending from visible light to near-infrared, it is important to solve not only the epitaxial growth of semiconductor lasers with different materials, grating preparation, waveguide etching, cavity surface coating, and other problems but also the structural design of an external optical frequency selective chip and the mode loss control of optical feedback.

In addition, it is crucial to design a special current/temperature drive control circuit for semiconductor lasers with different materials to ensure wavelength accuracy and frequency stability. In quantum optics, the laser frequency standard is the most commonly used light source. To achieve higher frequency stability, it is feasible to use a high-precision drive control circuit and an atomic gas chamber to build a feedback frequency stabilization system that locks the output frequency to the energy level of the atomic or molecular transition. However, the volume of the gas chamber used to provide the transition atoms is large and incompatible with the semiconductor process. Therefore, the realization of an integrated feedback frequency stabilization system for semiconductor lasers is a key problem that must be solved.

(5) Extra-large-scale and ultra-wideband antenna array communication theory and technologies

Extra-large-scale and ultra-wideband antenna array communication is a technology that simultaneously uses an extra-large-scale antenna array and ultra-wideband technology. It enhances the channel capacity and subsequently increases information transmission rates by increasing the number of antennas and expanding the bandwidth. Centimeter waves, millimeter waves, and terahertz frequency bands can provide hundreds of megahertz-level or even gigahertz-level ultra-wide bandwidths. Because of the shorter wavelengths of the carriers within these frequency bands, the antenna sizes are smaller, enabling a significant increase in the number of base station antennas, thus forming an extra-large-scale array. Extra-large-scale antenna array and ultra-wideband technology complement each other, and both are effective means to meet the information transmission rate requirements of 6G.

The spectrum is an important resource in mobile communication systems. With the advancements in communication technology, the bandwidth and frequency bands of communication systems have gradually increased. Research on millimeter-wave frequency bands for 5G has led to the development of mature communication-system models and transmission schemes. Early research on 6G focuses on the terahertz frequency bands above 100 GHz to provide an ultra-wide bandwidth. Because of characteristics such as high path loss and nonstationary channel space, most studies have focused on reducing the complexity and improving the accuracy of terahertz channel modeling. However, as the frequency increases, the path loss becomes more severe, limiting the coverage performance. In 2022, the 3GPP RAN#96 Conference officially defined the 6 425–7 125 MHz band as the U6G licensed spectrum and approved the Release 18 project for the full 6 GHz spectrum (5 925–7 125 MHz). In 2023, the Ministry of Industry and Information Technology released a new version of the "Radio Frequency Allocation Regulations of the People's Republic of China," which allocates the U6G frequency band to IMT (including 5G/6G) systems. This frequency band has relatively low path loss, strong electromagnetic wave diffraction, penetration capabilities, and excellent wireless coverage performance. Because of the limited attention paid to U6G, both academic and industrial communities have lacked substantial research on it. The channel model is unclear and is the focus of attention at this stage.

The channel characteristics of extra-large-scale antenna array systems have not been fully explored in different frequency bands, making channel measurement and modeling one of the primary research directions for extra-large-scale antenna array systems. Extra-high-dimensional channels exhibit spatial nonstationarities. Specifically, when wireless signals emitted by users reach the extra-large-scale antenna array, they form spherical wavefronts. In addition, the channel energy is concentrated only in a portion of the subarrays with significantly reduced dimensions. Most research on tasks, such as channel estimation, precoding techniques, and transceiver design, is based on this property. Furthermore, because of the large number of antennas, radio frequency, power consumption, and complexity in extra-large-scale antenna array systems cannot be ignored. Future research should focus on exploring low-cost system architectures and low-complexity transmission solutions.

(6) Optoelectronic in-sensor computing devices and their integration

Optoelectronic in-sensor computing devices and their integration refers to the integration of sensing, memory, and computing functions into optoelectronic devices and further large-scale integration. The optoelectronic in-sensor computing system addressed the speed and power limitations caused by the traditional von Neumann architecture and integrated optoelectronic sensing functions, thereby facilitating the development of more intelligent and energy-efficient computing systems. As a new intelligent device, the all-in-one optoelectronic fusion memory device can mimic the working mode of the human retina and brain. The device has highly adjustable conductivity and optical responsivity parameters because of the introduction of optoelectronic materials and the use of photons to control the transport characteristics of the carriers and ions. Image data processing speed and energy efficiency can be highly improved by integrating functions such as optical perception, information storage, and logical computing.

Traditional machine vision systems have high energy consumption and latency owing to the repeated movement of data between sensing, memory, and processing units, making it difficult to meet the real-time processing requirements for massive amounts of visual information. With the background of cloud computing, AI, and IoT, optoelectronic in-sensor computing technology has ushered in a huge development opportunity. It has a wide range of applications in automatic driving, wearable electronics, smart homes, and other areas, allowing for more efficient machine vision and brain-like computing.

Although the application prospects of optoelectronic in-sensor computing technologies are broad, there are many challenges in terms of performance, accuracy, and efficiency. For example, developing new functional composite materials to a achieve wide spectral response and constructing high-quantum-efficiency sensing and memory devices, exploring wafer-level processing techniques to achieve high-density integration of devices, and developing an intelligent optoelectronic in-sensor computing system to complete high-level information tasks.

(7) Automatic development of software assisted by artificial intelligence

The automatic development of software aided by artificial intelligence (AI) is a cutting-edge research field that uses AI techniques to assist, accelerate, and optimize the software development process. Its core objective is to reduce the workload of developers and improve the efficiency and quality of software development using intelligent methods. In recent years, the main research directions include the following:

1) Automated requirement analysis: This method uses machine learning and natural language processing techniques to automatically transform and analyze natural language requirements provided by users into requirement models that computers can directly understand and analyze. This can help developers more accurately understand and capture user requirements and reduce errors in understanding requirements.

2) Automated design and coding: This method uses machine learning and natural language processing techniques to automatically generate designs, or code fragments, functions, and even entire modules. This can help reduce the workload of manual design or coding and accelerate the development process.

3) Automated testing: This method uses AI techniques to automatically generate test cases, defect detection capabilities, and improve software testing coverage, thereby improving the software quality.

4) Automated integration and deployment: This method automatically integrates manually written code and automatically generated code by developers, and deploys it into the production environment, thereby improving software delivery efficiency and stability.

5) Intelligent recommendation system: This method recommends code, tools, and techniques that are suitable for the current development context based on the development-history data and project requirements of developers, thereby improving their development efficiency.

Generally, there are several development trends:

1) Intelligent coding: Code generation will become more intelligent and in line with developer intentions, reducing subsequent adjustments and modifications. It is also possible to automatically select the most suitable development strategy and tools based on the characteristics and needs of different projects, thereby providing more flexible and efficient intelligent development services.

2) Adaptive operation and maintenance: The ability to continuously optimize and improve the software operation process and quality of operation based on user feedback and changes in operation and maintenance data.

3) Collaborative development: Natural language processing and intelligent dialog techniques enable real-time interaction and communication with more developers, testers, and domain experts, promote cross-domain cooperation, provide a more friendly and efficient development experience, and create more comprehensive and optimized solutions.

4) Concealment of ethical and security issues: With the improvement of development automation, developers must pay more attention to the underlying ethical and security issues, ensuring that the automatically generated code and decisions are reliable and secure.

(8) Systematized gaming and intelligent control for multiagent systems

Systematized gaming and intelligent control for multiagent systems refers to the process by which intelligent agents adjust their behavior and optimize system parameters using game theory, interactive strategies, and intelligent control methods. This technology balances individual and group interests within the system. This topic faces challenges of complex system structures, uncertain game environments, incomplete decision-making information, and uninterpretable results. In this regard, current research hotspots focus on the following. ① Multiagent institutionalized and systematized game theory model. This study explores the game evolution law of multiagent systems by using and combining several AI learning algorithms. ② Modeling of multilevel, multiscale, multimode, nonlinear, and uncertain time-varying dynamic systems and analysis, simulation, prediction, optimization, and control of multiagent systems. ③ Multiagent autonomous navigation and swarm cooperation. This study addresses the issues of autonomy, intelligence, and scalability of multiagent systems, considering uncertain environments, incomplete decision information, and limited communication. ④ Decision-making processes in multiagent systems. This includes cooperative negotiation, resource allocation, and task assignment. Achieve effective collaboration and decision making among agents. ⑤ Robustness analysis framework for multiagent algorithms and models. Reduce the complexity of cooperative decision-making algorithms and address model biases between data-driven methods and real scenarios.

Overall, several problems require further investigation in the future. ① Enhance the interpretability and controllability of multiagent systems. Make system behavior and decision making more understandable and adjustable and improve system reliability and security. ② Integrate game theory, multiagent learning, and control theory. Promote game theory and intelligent control methods and improve overall system performance and intelligence. ③ Application of interdisciplinary research on game theory, learning, and control in emerging fields, such as intelligent transportation and logistics management.

(9) Cyber-physical security of industrial control systems

An industrial control system (ICS) is composed of various automated acquisition, monitoring, and control components for the automated operation and supervision of industrial infrastructure. ICSs include supervisory control and data acquisition (SCADA) systems, distributed control systems (DCS), and programmable logic controller (PLC) systems. Currently, ICSs are the nerve and operation center of national key infrastructure such as industrial production, smart grid, and smart transportation. The ICS has become a top target of adversaries because of their importance and openness. With the continuous improvement of attackers' vulnerability discovery capabilities and attack techniques, the cyber-physical security problem of ICS is becoming increasingly severe. It mainly refers to the security risks caused by attackers leveraging the characteristics of the tight integration of cyber space and physical space of ICS to launch coordinated attacks in the cyber and physical domains, leading to unobservable and uncontrollable dilemmas. For example, attackers can bypass defense methods to enhance cyber security, such as isolation and intrusion detection, and breakthrough physical security protection mechanisms, such as device redundancy. With these capabilities, attacks can penetrate across the ICS monitoring and control layers to destroy the physical process of the ICS. Such cyber-physical threats can use the characteristics of the physical processes of ICS to design malicious data tampering mechanisms that operate with strong collaboration and high concealment. This poses a significant challenge to ICS security.

Presently, studies related to the cyber-physical security of ICS have mainly focused on the following three aspects. ① Attacker capability modeling/system vulnerability analysis. These studies designed attack strategies from the attacker’s perspective based on the available knowledge of the ICS, such as its architecture, protocols, and control algorithms, thereby analyzing the vulnerabilities of ICSs. ② Attack detection. This method can detect malicious attacks by passively collecting dynamic data from the system or actively adding dynamic authentication information and then building a normal mode of the system. ③ Attack defense. This method includes defense strategies such as attack isolation, resilient control, and moving target defense. In the future, researchers will conduct vulnerability analysis and defense strategy design while considering the characteristics of large-scale, multilevel, and strong coupling of ICSs to enhance their cyber-physical security of ICSs.

(10) Chip-based satellite laser communication terminal

Satellite laser communication has the advantages of large bandwidth, high speed, concentrated emission energy, and strong anti-interference and anti-interception capabilities. It is currently the dominant position in the field of space network technology in which countries globally are vying for. The chip-based satellite laser communication terminal is a microdevice that realizes the function of satellite laser communication through optoelectronic integration technology. It integrates or partially integrates functional components, such as optoelectronic communication devices and electronic control units, into a single chip, resulting in a small size, lightweight, and low-power consumption. It can satisfy the diverse requirements of high-speed communication, data transmission, and satellite networking. In recent years, researchers have mainly focused on the following aspects. ① Heterogeneous optoelectronic integration technology. To improve chip performance by optimizing integrated chip design and manufacturing processes on silicon-on-insulator (SOI), silicon-based thin-film lithium niobate (LNOI), silicon nitride (Si_3N_4), indium phosphide (InP), and other material platforms. ② High-speed laser communication technology to solve key issues such as modulation, demodulation, codec, and signal processing of laser communication to improve the communication rate and transmission distance. ③ Optimize the reliability of the laser terminal to improve the signal anti-interference ability and environmental adaptability, such as temperature and radiation, and improve the stability and life. In the future, chip-based satellite laser communication terminals will be further integrated to achieve higher transmission rates, longer communication distances, higher reliability, and smaller and lighter terminals with lower power consumption. With the aim of multifunctional and networked communication, the compatibility and interoperability of laser terminals will be improved to promote the application and further development of chip-based satellite laser communication terminals in areas such as navigation, relay communication, Earth observation, deep-space exploration, and low-orbit internet constellations.

1.2 Interpretations for three key engineering research fronts

1.2.1 Theory and technology of large models and their computing systems

Large models and their computing systems learn the feature representation of the data from large-scale unlabeled data and pretrain the model with numerous parameters. It has the advantages of strong generalization, wide application scenarios, and low dependence on labeled data. However, because of the poor explain ability of the current large model, high dependence on training data, and high training and deployment costs, the theory and technology of large models and their computing systems urgently require breakthroughs in three aspects: theoretical framework, model structure, and training and deployment strategies.

First, there are two main trends in the theoretical framework of large models. One is to integrate information and over-parameterization theories in the research of large models, and explore the theoretical limit of the representation ability of large models such as generative pretrain transformers (GPT). Second, to introduce concepts involving graph theory into the theoretical analysis of large model training processes, such as using hypergraphs to explain and improve the stability of large model unsupervised bin-wise pretraining. The main research institutions in this direction include Harvard University, Tsinghua University, Zhejiang University, Hikvision Digital Technology Co., Ltd., and Warsaw University.

Second, an important research trend in large model structure design is the cooperation of large model structures with transfer learning strategies to solve the degradation and bias of large models caused by unfiltered data, thereby improving their predictive ability of large models. The other is to introduce the concept of prompt programming into the model design to reduce the overfitting phenomenon of large models in the bottom and middle layers, and to guide the model to better understand and perform specific tasks through well-designed prompts. The main research institutions in this direction include the Facebook AI Research Institute, Seoul National University, and the National Kaohsiung University of Applied Sciences.

In addition, in terms of training and deployment strategies for large models, the use of new hardware such as McDRAM to accelerate the real-time performance of large model inference and the energy consumption ratio of the deployment process is a potential technology for deploying large models on edge devices. In addition, using approximate computing technology to accelerate the inference process or designing customized binarization strategies and quantization methods for large models may effectively improve their inference speed and save computing resources in the future. Major research institutions in this area include the University of Bremen, the National University of Singapore, Huawei Technologies Co., Ltd., and the University of Sydney.

Table 1.2.1 shows the distribution of the main output countries of core papers in the engineering research front of “theory and technology of large models and their computing systems”. The USA has the highest number of core papers globally, accounting for approximately one-third of all papers. China is second only to the USA, but the average publication year of papers is newer, indicating a state of rapid catching up. China’s international cooperation partners are mainly the USA and Australia (Figure 1.2.1). Four of the Top 10 output institutions (Table 1.2.2) are from China, with the rest located in the USA, Australia, Singapore, and other countries. In terms of institutional cooperation (Figure 1.2.2), the three Chinese institutions have relatively close cooperation with the University of Sydney, while the three domestic institutions have relatively close cooperation. In terms of the number of citing papers (Table 1.2.3), China ranked first (accounting for 44.56%), followed by the USA, and the remaining countries accounted for less than 10%. Except for Harvard University, which ranks seventh, all the Top 10 institutions that produce citing papers are from China (Table 1.2.4), reflecting the high attention of Chinese scientific research institutions to the theory and technology of large models and their computing systems.

Over the past five years, many research results in the theory and technology of large models and their computing systems have been achieved. However, in terms of the overall development process of the research field, their application and research are still in their infancy, and many key bottlenecks must be resolved urgently. Figure 1.2.3 shows the key development directions for the next 5–10 years.

First, model compression and distributed training. Currently, large models represented by ChatGPT contain more than 10 billion parameters, necessitating huge computing and storage resources. Future development directions include more efficient model compression and acceleration technologies to reduce the parameter scale and computational cost of the model, improve its deployment efficiency on edge devices, such as laptops and mobile phones, and realize real-time inference and decision making in various computing scenarios. Conversely, as the scale of models grows, distributed training and collaborative learning of large models will be critical, and new distributed training strategies and techniques will help speed up model training while maintaining model performance.

Second, automated and smarter model design. Currently, large enterprises such as Google and Microsoft rely on their powerful computing resources to design multi-input multiple-output large-scale model structures, such as T5 and Kosmos. However,

Table 1.2.1 Countries with the greatest output of core papers on "theory and technology of large models and their computing systems"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	11	32.35	1 664	151.27	2019.0
2	China	9	26.47	419	46.56	2021.0
3	Australia	3	8.82	410	136.67	2019.3
4	Germany	3	8.82	129	43.00	2019.3
5	UK	3	8.82	14	4.67	2022.0
6	Poland	2	5.88	63	31.50	2021.0
7	Singapore	2	5.88	14	7.00	2020.0
8	India	2	5.88	11	5.50	2020.5
9	Saudi Arabia	1	2.94	51	51.00	2019.0
10	Republic of Korea	1	2.94	18	18.00	2020.0

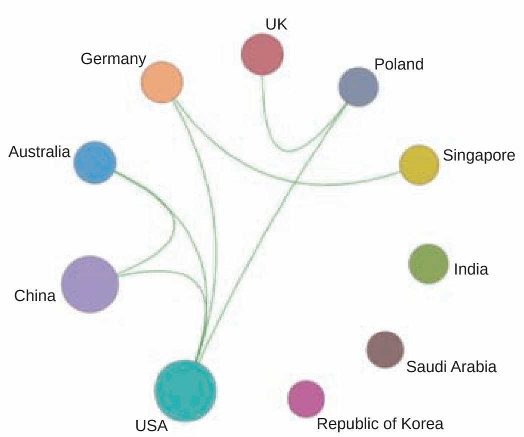

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "theory and technology of large models and their computing systems"

Table 1.2.2 Institutions with the greatest output of core papers on "theory and technology of large models and their computing systems"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Facebook AI Research	2	5.88	1 320	660.00	2019.0
2	The University of Sydney	2	5.88	396	198.00	2019.0
3	Harvard University	2	5.88	118	59.00	2019.0
4	University of Warsaw	2	5.88	63	31.50	2021.0
5	Zhejiang University	2	5.88	18	9.00	2021.5
6	National University of Singapore	2	5.88	14	7.00	2020.0
7	Huawei Technologies Co., Ltd.	1	2.94	346	346.00	2021.0
8	Peking University	1	2.94	346	346.00	2021.0
9	Peng Cheng Laboratory	1	2.94	346	346.00	2021.0
10	Humboldt University of Berlin	1	2.94	113	113.00	2017.0

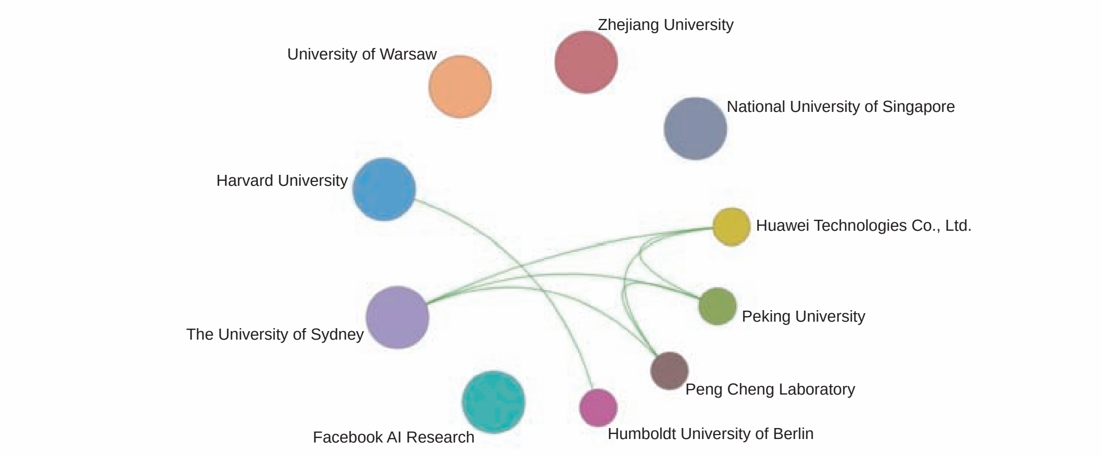

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "theory and technology of large models and their computing systems"

Table 1.2.3 Countries with the greatest output of citing papers on "theory and technology of large models and their computing systems"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 089	44.56	2021.4
2	USA	557	22.79	2021.0
3	Republic of Korea	142	5.81	2021.3
4	UK	125	5.11	2021.2
5	Germany	106	4.34	2021.1
6	Canada	86	3.52	2020.9
7	Australia	83	3.40	2021.3
8	India	79	3.23	2021.6
9	Japan	76	3.11	2021.1
10	France	55	2.25	2021.0

Table 1.2.4 Institutions with the greatest output of citing papers on "theory and technology of large models and their computing systems"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	103	22.01	2021.3
2	Tsinghua University	54	11.54	2021.3
3	Peking University	43	9.19	2021.3
4	Shanghai Jiao Tong University	42	8.97	2021.3
5	Zhejiang University	37	7.91	2021.3
6	The Chinese University of Hong Kong	34	7.26	2020.5
7	Harvard University	34	7.26	2020.3
8	University of Electronic Science and Technology of China	33	7.05	2021.2
9	Wuhan University	33	7.05	2021.6
10	Harbin Institute of Technology	28	5.98	2021.7

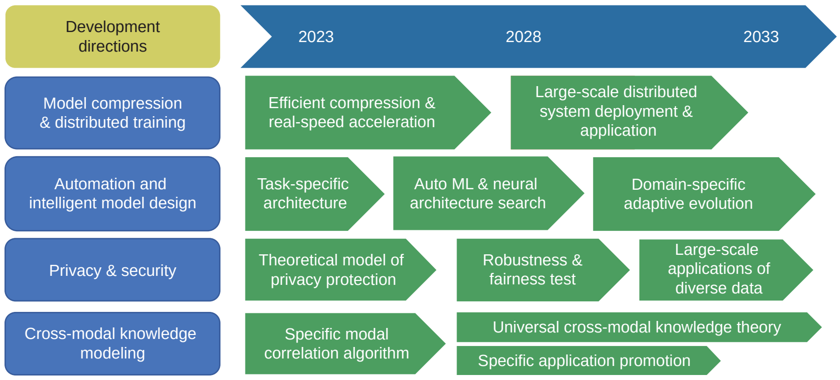

Figure 1.2.3 Roadmap of the engineering research front of “theory and technology of large models and their computing systems”

methods such as reinforcement learning and evolutionary algorithms can be used to automatically design efficient model structures suitable for specific tasks. Therefore, automated neural architecture search and model optimization technologies will be developed in the field of large models in the future. In addition to Huawei’s Pangu, Baidu’s ERNIE Bot, Zhiyuan’s WuDao, and other general-purpose pretraining models, the future will inevitably require more pretraining models for specific fields such as medical care and finance.

Third, privacy and security. With the increasing number of applications based on large models, such as ChatGPT and Dell-E, the privacy of large models has gradually attracted more attention. Future research directions include maintaining high performance of the model while protecting user data privacy. In terms of security, the robustness and fairness of large models will be the focus of future research, including how to make the model perform well on diverse data while avoiding bias against different groups.

Fourth, modeling and reasoning of cross-modal knowledge. Existing technology has enabled the correlation and generation of multimodal data such as images, texts, and audio. However, when faced with more complex and abstract reasoning scenarios, such as protein structure, real-time automatic driving, and multiparty games, existing large models, such as BAI-Chem and Pangu, can only answer questions based on inductive associations in a large amount of training data. To make large models closer to human intelligence, future research will focus on the following: ① quantitative modeling and expression of knowledge in large cross-modal models; ② exploring the relationship between reasoning decisions and knowledge representation in large models; ③ reasonability and interpretability of model multimodal knowledge.

1.2.2 Networking theories and key technologies of satellite internet

Satellite internet is a new revolution in the internet field with global coverage, on-demand access, on-demand service, secure communication, and reliable communication. It provides strong support for the prospect of global interconnection; therefore, it has attracted the interest of many countries. In the 1990s, Motorola Company in the US established the Iridium Satellite System, which consists of 66 low-orbit satellites with inter-satellite links and onboard processing capabilities. Meanwhile, Laura and Qualcomm Companies in the US have built a global satellite system that includes 48 low-orbit satellites, each of which employs transparent forwarding. These two satellite internet systems have undergone bankruptcy restructuring for commercial reasons. After a period of downtime, the satellite internet has recently set off its second craze on an even larger scale. In 2017, the British company OneWeb proposed the OneWeb project, which plans to launch 1 980 satellites to constitute a low-orbit constellation with global coverage. Furthermore, the American company SpaceX plans to launch 42 000 low-orbit satellites to form star links capable of supporting high-speed mobile communication globally. In recent years, China has accelerated the construction of the satellite internet. For example, the “Hongyan Constellation” designed by the China Aerospace Science and Technology Corporation includes 324 satellites, whereas the “Hongyun Constellation” designed by the China Aerospace Science and Industry Corporation includes 156 satellites.

Although satellite internet has grown rapidly, many challenging issues still exist, including network architectures, routing protocols, inter-satellite communication, and mobility management, which are presented as follows.

1) In terms of network architecture, there are currently two main architectures. The first type is the nonterrestrial network (NTN), which is led by 3GPP, the international organization for the standardization of mobile communication. This open architecture is compatible with existing terrestrial cellular networks and is an integral part of the entire 6G network. The other architecture was specifically designed for the Starlink project by SpaceX Company, which has a closure property. The main research institutions in this area include the Harbin Institute of Technology, the Chinese Academy of Sciences, and Waseda University, Huawei.

2) In terms of routing protocols, new elastic routing protocols must be developed because satellite networks are highly dynamic, satellite positions constantly vary, and ground network routing protocols are inapplicable. The basic idea is to use the regularity of the constellation motion to map real satellite nodes to virtual nodes. When satellites move or the ground terminal switches, the routing table between virtual nodes is exchanged between physical nodes; thus, the routing information exchange can be completed. The main research institutions in this direction include the University of Surrey, SpaceX, Beijing University of Posts and Telecommunications, Xidian University, the National University of Defense Technology, and Beijing Institute of Technology.

3) In terms of inter-satellite communication, there are mainly two development trends. The first is inter-satellite microwave communication, which is highly technologically mature and currently has broad applications. However, microwave communication has difficulty meeting the requirements of high-speed communications and has limitations such as limited frequency band capacity and severe co-frequency interference. The second is inter-satellite laser communication, which is widely used in the new-generation satellite internet. Compared with microwave communication, laser communication has several advantages, including large bandwidth, low communication payload, strong anti-interference ability, and good confidentiality. The main research institutions in this direction include the University of Surrey, SpaceX, Chinese Academy of Sciences, Beijing University of Posts and Telecommunications, University of Electronic Science and Technology, and Zhejiang University.

4) In terms of mobility management, one option is to use centralized mobility management, in which local agents manage terminals. Each time a terminal initiates a location update, the messages are transmitted to local agents. Another option is to use distributed mobility management, in which the Earth is divided into multiple zones, where terminals can register to a virtual gateway composed of satellite clusters covering that zone. Therefore, large-scale satellite network mobility management can be achieved. The main research institutions in this direction include Peng Cheng Laboratory, Southeast University, University of Luxembourg, Huawei, and ZTE Corporation.

Table 1.2.5 shows the main countries that output core papers in this cutting-edge field. China has an obvious advantage, ranking first in the world in terms of the number of core papers with over 67% proportion, and cooperates with Japan, the UK, Saudi Arabia, Republic of Korea, Canada, Australia, and Norway (Figure 1.2.4). The Chinese Academy of Sciences, and Harbin Institute of Technology jointly rank first among the Top 10 institutions that output core papers (Table 1.2.6). Seven institutions are from China, and the rest are from Saudi Arabia, Japan, and Luxembourg. In terms of institutional cooperation (Figure 1.2.5), King Abdulaziz University, Waseda University, and Xi'an University of Posts and Telecommunications have close cooperation. In terms of the number of cited core papers (Table 1.2.7), China still ranks first, with more than 50%, while other countries account for less than 10%. The Top 10 institutions that output cited core papers (Table 1.2.8) were mostly from China, except Waseda University, which ranked sixth, reflecting the strong research strength of China in this field.

Currently, satellite internet is highly valued by major countries and is developing at an unprecedented speed. The development roadmap for this frontier is shown in Figure 1.2.6. The following paragraphs outline its development trends in four areas: network architecture, routing protocols, inter-satellite communication, and mobility management. In terms of network architecture, the NTN architecture is currently in the discussion and standard-setting stage and is expected to be fully developed and commercialized by 2027. In terms of routing protocols, the currently used fixed routing protocols have inherent flaws that seriously constrain the scale and performance of networks, whereas elastic network protocols are gradually improving and are expected to mature by approximately 2026. In terms of inter-satellite communication, microwave communication currently used has low

Table 1.2.5 Countries with the greatest output of core papers on "networking theories and key technologies of satellite internet"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	21	67.74	1 097	52.24	2020.4
2	Japan	4	12.90	350	87.50	2020.8
3	UK	4	12.90	139	34.75	2021.5
4	Saudi Arabia	3	9.68	141	47.00	2021.3
5	Italy	3	9.68	119	39.67	2020.7
6	Republic of Korea	3	9.68	57	19.00	2021.0
7	Canada	3	9.68	16	5.33	2022.0
8	Australia	2	6.45	72	36.00	2020.5
9	Luxembourg	2	6.45	49	24.50	2020.0
10	Norway	1	3.23	89	89.00	2020.0

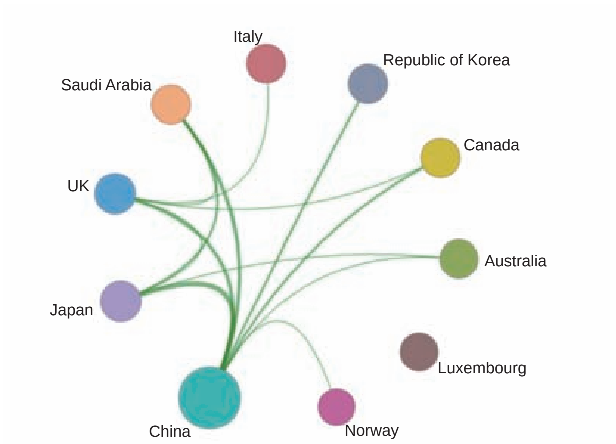

Figure 1.2.4 Collaboration network among major countries in the engineering research front of "networking theories and key technologies of satellite internet"

Table 1.2.6 Institutions with the greatest output of core papers on "networking theories and key technologies of satellite internet"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	3	9.68	154	51.33	2019.0
2	Harbin Institute of Technology	3	9.68	91	30.33	2020.3
3	King Abdulaziz University	2	6.45	137	68.50	2021.0
4	Waseda University	2	6.45	137	68.50	2021.0
5	Xi'an University of Posts and Telecommunications	2	6.45	137	68.50	2021.0
6	Beijing Institute of Technology	2	6.45	102	51.00	2021.0
7	Peng Cheng Laboratory	2	6.45	87	43.50	2019.5
8	Xidian University	2	6.45	71	35.50	2020.5
9	Beijing University of Posts and Telecommunications	2	6.45	63	31.50	2021.0
10	University of Luxembourg	2	6.45	49	24.50	2020.0

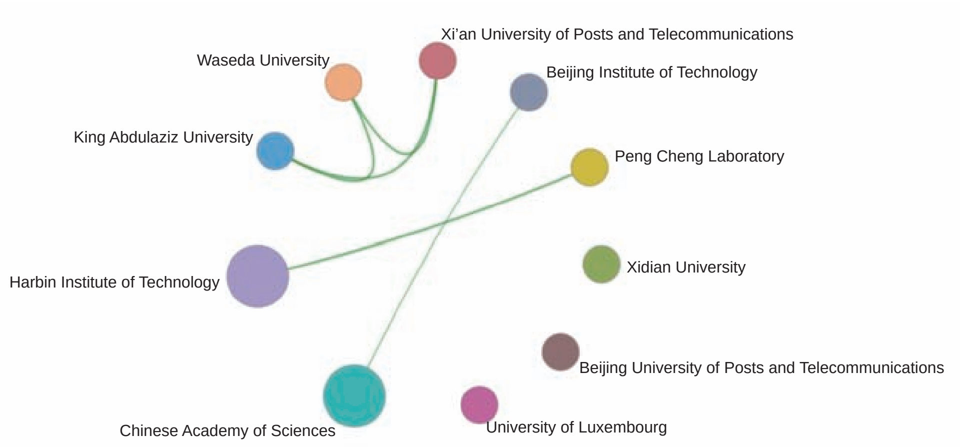

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “networking theories and key technologies of satellite internet”

Table 1.2.7 Countries with the greatest output of citing papers on “networking theories and key technologies of satellite internet”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	667	51.91	2021.3
2	Canada	100	7.78	2021.5
3	USA	87	6.77	2021.3
4	UK	77	5.99	2021.3
5	Japan	67	5.21	2021.5
6	India	64	4.98	2021.6
7	Republic of Korea	53	4.12	2021.7
8	Saudi Arabia	48	3.74	2021.6
9	Australia	48	3.74	2021.4
10	Italy	41	3.19	2021.0

Table 1.2.8 Institutions with the greatest output of citing papers on “networking theories and key technologies of satellite internet”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Harbin Institute of Technology	70	16.09	2021.2
2	Beijing University of Posts and Telecommunications	63	14.48	2021.0
3	Xidian University	44	10.11	2021.5
4	Peng Cheng Laboratory	39	8.97	2021.4
5	Chinese Academy of Sciences	37	8.51	2021.2
6	Waseda University	34	7.82	2021.6
7	Southeast University	32	7.36	2021.2
8	Beijing Institute of Technology	30	6.90	2021.6
9	National University of Defense Technology	30	6.90	2021.1
10	University of Electronic Science and Technology of China	29	6.67	2021.4

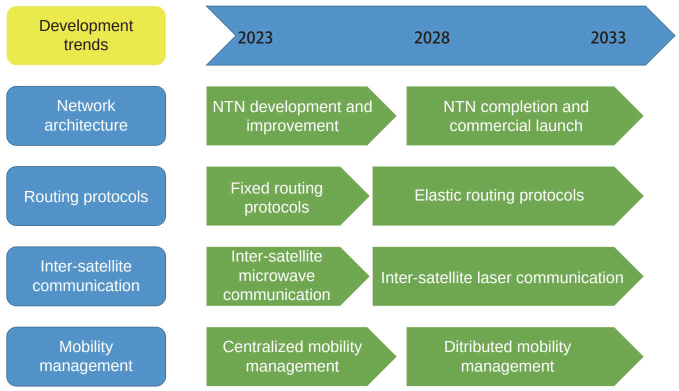

Figure 1.2.6 Roadmap of the engineering research front of "networking theories and key technologies of satellite internet"

communication rates and strong interference and is gradually being replaced by inter-satellite laser communication, which is expected to be completed by 2026. In terms of mobility management, the existing centralized management is transitioning to distributed management because of its high signaling overhead and transmission latency. The development trend of satellite internet is summarized as follows. First, the satellite internet has shifted from focusing on communication to integrating communication, navigation, and remote sensing, allowing for a multifunctional satellite internet. Second, satellite internet has developed from ground-devices-assisted access to mobile satellite communication without a ground station, achieving the goal of on-demand access. Third, has developed from satellite internet to satellite IoT to achieve the vision of the interconnection of all things. In terms of the application scenarios of satellite internet, has been used in emergency communication, remote area communication, and logistic communication. With the rapid development of the satellite internet, it will be widely used in various fields such as the economy, society, and military in the future.

1.2.3 Ultra-large-scale silicon-based quantum chips

A quantum chip is a device designed and manufactured based on the principles of quantum mechanics for applications in quantum computing and communications. Unlike classical chips, which use binary bits, quantum chips use quantum bits (qubits) as their fundamental information units. Qubits can exist in superpositions 0 and 1, and they can share information among multiple qubits through entanglement. This characteristic endows quantum chips with significant advantages in addressing specific problems, allowing them to solve certain computationally challenging tasks, such as large-integer factorization, quantum simulation, and optimization, at faster speeds than classical computers. Fabricating and manipulating quantum chips are a challenging because of the fragility of quantum bits, which are susceptible to destruction by uncontrollable environmental influences. A universal quantum computer often requires a substantial number of qubits to implement a quantum error correction and achieve the desired quantum advantage. Nevertheless, in terms of the number of qubits alone, various physical implementations, including superconducting circuits, diamond nitrogen-vacancy centers, and trapped ion technologies, are yet to meet these demands. Consequently, the production of large-scale quantum chips containing millions of qubits has emerged as a critical challenge for the realization of universal quantum computing. Given the successful manufacture of chips containing billions of transistors within the traditional semiconductor industry, the integration of silicon-based electronics with quantum technology holds the promise of establishing a quantum computing platform for the existing semiconductor manufacturing infrastructure. The compatibility of silicon-based quantum chips with traditional semiconductor processes provides advantages in terms of production cost, scalability, and integration. This has propelled large-scale silicon-based quantum chips into a focal point of research in the field of quantum computing, offering a promising pathway for the feasibility and scalability of quantum computing.

Silicon-based quantum chips present various development routes. One approach involves encoding quantum information into electron (hole) spins confined in gate-defined silicon quantum dots or implanted phosphorus nuclear spins embedded in silicon. In

1998, theoretical physicists predicted that spin states within silicon nanostructures could serve as carriers of quantum information, marking the inception of an experimental research race. Single-qubit operations can be achieved by manipulating and measuring the individual electron spins. Leveraging the exchange interaction between the two spins enables the implementation of two-qubit gate operations. Initial experiments used III–V semiconductor materials; however, unavoidable hyperfine interactions hindered their further advancement. In 2013, several research groups simultaneously reported breakthroughs in silicon-based spin qubits. This was facilitated by the isotopic purification of silicon to suppress hyperfine interactions, resulting in a significant enhancement in fidelity. Currently, single-qubit and two-qubit gates with fidelity far exceeding the error-correction thresholds have been realized. Furthermore, because of the nanoscale physical dimensions of silicon quantum dots and dopant atoms and their compatibility with modern IC technology, they can be scaled up to large-scale qubit arrays with reasonable chip footprints. Quantum processors comprising six qubits have already been demonstrated as larger quantum dot platforms in one-dimensional and two-dimensional configurations.

Another approach is to use silicon-based photonic integration processes to achieve quantum entanglement between photons and quantum-state manipulation, thereby enabling quantum computing and communications. Photonic quantum technology stands out because of its advantages, such as longer decoherence time, multiple degrees of freedom, no need for vacuum, and low temperature. In contrast to the bulky, unstable, and poorly scalable traditional optical instruments, silicon-based photonic chips fabricated using CMOS nanomanufacturing techniques offer high integration, stability, controllability, and scalability. Currently, integration of several hundred optical components on a single chip has been achieved, and it is expected that various core photonic quantum functionalities, including quantum light sources, quantum control pathways, and single-photon detectors, can be integrated on a single chip. In recent years, silicon-based photonic chips achieved made significant breakthroughs in the fields of boson sampling, multiphoton high-dimensional quantum entangled states, quantum key distribution, and quantum teleportation.

In recent years, there have been numerous significant achievements in the field of large-scale silicon-based quantum chips. The countries and institutions contributing to the key research papers are outlined in Tables 1.2.9 and 1.2.10. The USA, the UK, and Netherlands rank among the top three nations in terms of the number of key research papers published. Prominent contributing institutions include Delft University of Technology, University of Bristol, and Peking University. Furthermore, many of these key research papers resulted from collaborations between various research institutions across different countries, as illustrated by the collaboration networks between leading countries and institutions in Figures 1.2.7 and 1.2.8. Tables 1.2.11 and 1.2.12 list the main countries and institutions responsible for citing key papers in this field. The Chinese Academy of Sciences and University of Science and Technology of China rank the top two, reflecting China’s notable interest and engagement in this direction.

From the perspective of the overall development trajectory within the field, ultra-large-scale silicon-based quantum chips are still in their nascent stages and many key problems must be solved. As depicted in Figure 1.2.9, future development of ultra-large-scale silicon-based quantum chips will focus on the following key directions:

(1) Silicon-based spin quantum chips

1) Large-scale arrays: The practical realization of spin quantum chips requires increasing the fidelity of the initialization, manipulation, and readout modules for each qubit to sufficiently high levels. Large-scale fabrication of high-fidelity qubits using CMOS technology is difficult because the properties of spin qubits, such as valley splitting, spin-orbit coupling, and tunneling coupling between quantum dots, are very sensitive to atomic-level defects. Therefore, the quality of the material growth is crucial. Rapid detection and automated control of each qubit’s parameters are also essential.

2) Long-range coupling: Currently, most silicon-based spin qubits rely on nearest-neighbor coupling, which requires proximity between quantum dots or phosphorus-doped atoms, limiting the layout of the dense arrays. Developing methods for long-range coupling can enable the separation of qubits to over larger distances. Several experimental approaches have been explored, including floating gates, microwave cavities, superconducting resonators, and electron shuttling.

Table 1.2.9 Countries with the greatest output of core papers on “ultra-large-scale silicon-based quantum chips”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	24	42.86	3 059	127.46	2019.7
2	UK	15	26.79	2 436	162.40	2018.7
3	Netherlands	13	23.21	2 135	164.23	2019.5
4	Australia	12	21.43	1 441	120.08	2019.7
5	China	11	19.64	1 603	145.73	2019.5
6	Japan	11	19.64	1 075	97.73	2020.1
7	Germany	9	16.07	1 621	180.11	2019.8
8	Denmark	6	10.71	748	124.67	2020.3
9	Republic of Korea	4	7.14	542	135.50	2019.5
10	Switzerland	4	7.14	226	56.50	2021.2

Table 1.2.10 Institutions with the greatest output of core papers on “ultra-large-scale silicon-based quantum chips”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Delft University of Technology	11	19.64	1 940	176.36	2019.5
2	University of Bristol	9	16.07	1 319	146.56	2018.6
3	Peking University	6	10.71	753	125.50	2020.2
4	Technical University of Denmark	6	10.71	748	124.67	2020.3
5	Netherlands Organization for Applied Scientific Research	6	10.71	577	96.17	2020.0
6	QuTech	5	8.93	493	98.60	2019.8
7	The University of New South Wales	5	8.93	492	98.40	2019.6
8	University of Stuttgart	4	7.14	902	225.50	2020.0
9	Heriot-Watt University	4	7.14	741	185.25	2019.0
10	University of Electronic Science and Technology of China	4	7.14	693	173.25	2018.5

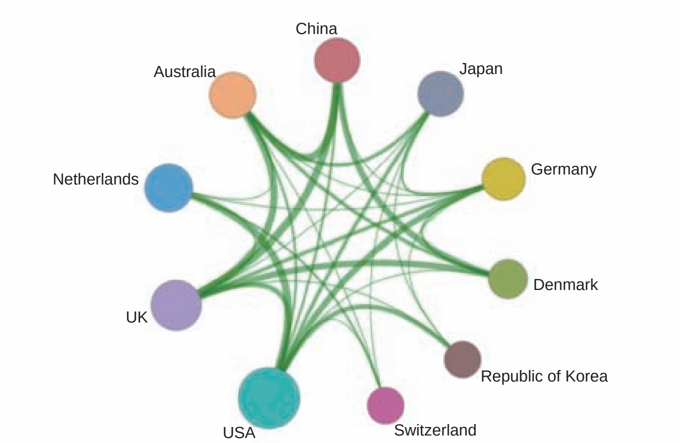

Figure 1.2.7 Collaboration network among major countries in the engineering research front of “ultra-large-scale silicon-based quantum chips”

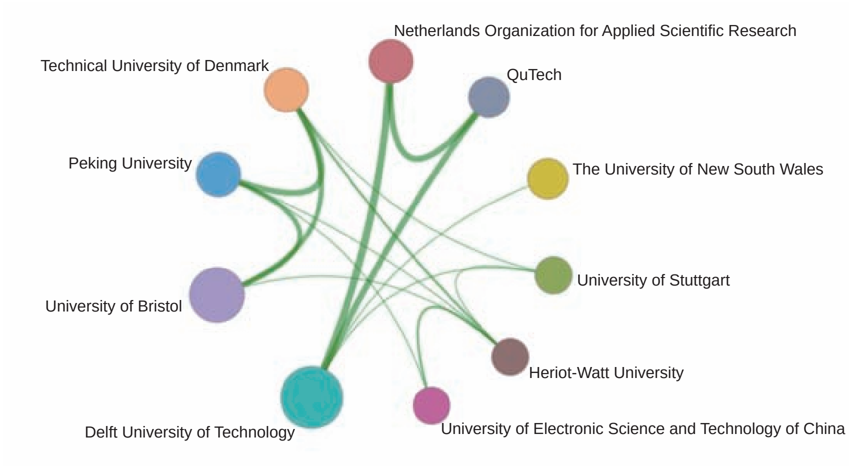

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “ultra-large-scale silicon-based quantum chips”

Table 1.2.11 Countries with the greatest output of citing papers on “ultra-large-scale silicon-based quantum chips”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	USA	1 281	23.69	2020.6
2	China	1 157	21.40	2020.8
3	Germany	558	10.32	2020.7
4	UK	461	8.53	2020.4
5	Australia	412	7.62	2020.4
6	Japan	325	6.01	2020.6
7	Canada	302	5.59	2020.4
8	France	273	5.05	2020.5
9	Italy	232	4.29	2020.6
10	Netherlands	207	3.83	2020.5

Table 1.2.12 Institutions with the greatest output of citing papers on “ultra-large-scale silicon-based quantum chips”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	225	16.78	2020.6
2	University of Science and Technology of China	213	15.88	2020.7
3	Delft University of Technology	145	10.81	2020.4
4	The University of New South Wales	112	8.35	2020.5
5	Massachusetts Institute of Technology	111	8.28	2020.6
6	Harvard University	103	7.68	2020.2
7	University of Technology Sydney	93	6.94	2020.6
8	Université Grenoble Alpes	89	6.64	2020.8
9	University of Bristol	85	6.34	2019.9
10	The University of Maryland	84	6.26	2020.4

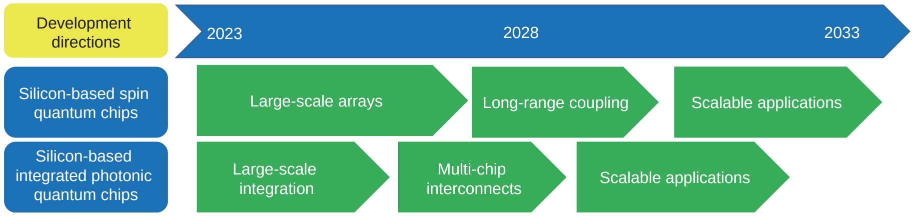

Figure 1.2.9 Roadmap of the engineering research front of “ultra-large-scale silicon-based quantum chips”

(2) Silicon-based integrated photonic quantum chips

1) Large-scale integration: Integrating quantum light sources, quantum-state manipulation pathways, and single-photon detectors on a single chip while meeting all the key performance metrics remains a challenge. It is critical to reduce the losses caused by the interaction between photons and the surrounding medium within the chip. In addition, to realize practical applications, the complexity of the multiphoton high-dimensional entangled states that photonic quantum chips can generate must be continuously improved to achieve a sufficiently large state space.

2) Multichip interconnects: As the number of qubits increases, it becomes increasingly difficult to integrate more optical components on a single chip. Future developments may leverage the advantages of optical communication to achieve interconnectivity between multiple chips, thereby enabling the construction of large-scale quantum processors through distributed quantum computing. However, achieving high performance interconnects between silicon-based integrated photonic quantum chips remains a technical challenge, thereby necessitating the development of ultralow-loss interconnect technologies to enhance the fidelity of quantum-state transmission between chips.

Ultra-large-scale silicon-based quantum chips have tremendous potential in various applications. Both silicon-based spin quantum chips and silicon-based integrated photonic quantum chips are poised to become pivotal components of future quantum technologies, with profound implications for solving complex problems and enhancing information security. In the future, silicon-based quantum chips will continue to progress toward greater scalability and broader applications owing to their compatibility with traditional CMOS technology.

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

The Top 10 engineering development fronts in the information and electronic engineering field are summarized in Table 2.1.1, 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. “Light-controlled phased-array technology”, “control technology of unmanned systems based on brain–computer interface”, and “artificial-intelligence-based fault diagnosis and detection” are fronts of data mining. The remaining fronts of expert nomination. The annual number of core patents published for the Top 10 engineering development fronts from 2017 to 2022 is listed in Table 2.1.2.

(1) Light-controlled phased-array technology

A light-controlled phased-array antenna (LCPAA) mainly includes transmitting-receiving (TR) modules, an antenna array, light-sensitive components, and a light-controlling module, in which the radiation characteristics of the LCPAA are engineered by manipulating the electromagnetic response of light-sensitive materials (and/or components) in the space-/time-/frequency-/spectrum-domains through light. Without loss of generality, the controlling parameters can be the intensity, wavelength, beam

Table 2.1.1 Top 10 engineering development fronts in information and electronic engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Light-controlled phased-array technology	260	1 063	4.09	2020.0
2	Control technology of unmanned systems based on brain–computer interface	464	1 344	2.90	2019.8
3	Computing power network construction technology for diverse computing	638	3 034	4.76	2019.9
4	Flexible intelligent tactile sensor	616	5 105	8.29	2019.1
5	High-speed free-space optical communication technology	1 018	2 061	2.02	2020.1
6	Terahertz solid-state phased-array integrated circuit	887	2 022	2.28	2019.9
7	Artificial-intelligence-based fault diagnosis and detection	991	5 736	5.79	2020.9
8	Large-size silicon carbide materials and power chips	232	366	1.58	2020.1
9	Naked eye 3D technology based on light-field technology	668	3 379	5.06	2019.0
10	Augmented reality space operating system	420	1 949	4.64	2019.9

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in information and electronic engineering

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Light-controlled phased-array technology	25	37	46	42	39	71
2	Control technology of unmanned systems based on brain–computer interface	58	78	73	67	88	100
3	Computing power network construction technology for diverse computing	77	77	109	125	101	149
4	Flexible intelligent tactile sensor	127	136	96	107	82	68
5	High-speed free-space optical communication technology	115	138	127	128	214	296
6	Terahertz solid-state phased-array integrated circuit	94	112	162	133	176	210
7	Artificial-intelligence-based fault diagnosis and detection	18	38	99	151	293	392
8	Large-size silicon carbide materials and power chips	26	27	21	43	46	69
9	Naked eye 3D technology based on light-field technology	168	154	106	89	75	76
10	Augmented reality space operating system	47	61	72	63	79	98

direction, time light delay, or a combination of these. The LCPAA has been widely used in wireless communication, remote sensing, positioning, precision detection, and other applications. Depending on the frequency at which the radiation occurs, LCPAA technology mainly involves two categories: ① optical phased-array (OPA) for optical communication and optical sensing (such as laser radars), which is also known as space-light modulation; ② microwave-optical phased array for microwave communication, detection, and sensing (such as microwave radars). Low cost, high efficiency, wide angular view, large bandwidth, and high space-time resolution are highly desirable characteristics of the two types of LCPAAs.

To clarify, the microwave-optical phased array has two subcategories: ① microwave-photonic phased arrays (MPPA) and ② optically tuned microwave phased arrays (OTMPA). The MPPA uses time-delay light as a microwave carrier for wideband low-loss microwave transmission, but it faces challenges such as the compact integration of a light–microwave converter, precision time-delay of optical waveguides, scalable microwave-photonic transmission modules, and a compact yet high-power laser source. However, OTMPA addresses the critical challenges of achieving multipolarized high gain at high frequency using light-induced microwave modulation, thereby eliminating the need for complex feeding networks and high-cost precision fabrication in conventional electrically tuned phased arrays. Further improvement in the performance of OTMPAs requires high-speed optical-microwave switches, high-contrast light-sensitive materials, and innovative architecture design for high-precision control of the microwave phase by light. On the optical radiation side, the current research trend of OPA mainly focuses on the development of light delay and light-modulators for multiple-light-beamforming, where various light-modulation mechanisms have been proposed, such as heat, mechanical, electrical, liquid–crystal, and phase-changing modulations.

(2) Control technology of unmanned systems based on brain–computer interface

The brain–computer interface-based control technology of the unmanned system combines neurobiology, informatics, AI, and unmanned systems to collect and analyze physiological signals generated by brain activity. It decodes human brain intentions and converts them into control commands, which are then encoded to enable interaction and control between the human brain and the unmanned systems. With this technology, users can directly control unmanned systems using physiological signals, such as electroencephalography (EEG), without the need for traditional human–computer interaction.

The main technical directions are as follows:

1) Acquisition and transmission of brain signals: Different types of biosensors (such as electroencephalographs and eye trackers) are used to capture physiological information from the human brain. The signals are amplified and converted into digital signals.

2) Processing and decoding of brain signals: To identify feature patterns in brain signals and decode human brain intentions, complex and high-dimensional brain activity data are processed using signal processing methods such as noise reduction and feature extraction.

3) Commands generation and control of unmanned systems: The identified feature patterns of human brain intentions are converted into corresponding control commands using encoding techniques. These commands are used to control unmanned systems such as drones, autonomous vehicles, robots, and exoskeletons. In addition, it is important to ensure the comfort, convenience, stability, and real-time nature of human–computer interaction.

Traditional unmanned systems based on AI have limitations in responding to some abnormal states that are of low probability. To address this issue, the integration of the brain–computer interface (BCI) into unmanned systems leverages the fusion of brain–computer intelligence, fully leveraging the advantages of human and computer intelligence. This approach opens a new avenue for enhancing the intelligence of unmanned systems. It is expected to have broad application prospects in fields such as aviation, aerospace, navigation, autonomous driving, traffic safety, elderly and disability assistance, medical support, rescue operations, industrial control, education, and entertainment.

(3) Computing power network construction technology for diverse computing

Computing power networks are technical concepts that connect cross-center computing power through networks. They rely on high-speed, mobile, secure, and ubiquitous network connections that integrate multilevel computing resources, such as the net, cloud, number, intelligence, security, edge, end, and chain. China was the first country to propose this new type of integrated basic service that combines data sensing, transmission, storage, and computing. Its goal is to integrate multilevel computing resources and build a new infrastructure system centered on computing and networking. Computing power network construction technology for diverse computing refers to the use of high-performance and cloud computing, high-performance networks, distributed storage, and other technical means to effectively integrate and schedule heterogeneous computing resources and provide users with flexible, efficient, and scalable computing, storage, network, application, and data services. This technology meets the demands for diversity and dynamism of computing resources in different application scenarios to support complex computing tasks in AI, big data analysis, virtual reality, and other fields.

The main technical directions include heterogeneous resource integration and collaboration, computing resource and service encapsulation, intelligent task scheduling, and dynamic metering and billing. Heterogeneous resource integration and collaboration connect heterogeneous and network computer resources through unified interfaces and protocols to form a unified computing resource pool and provide users with a flexible and scalable computing environment. Computing resources and service encapsulation describe, encapsulate, and invoke the underlying cloud platform resources. Intelligent task scheduling designs reasonable scheduling algorithms and load-balancing strategies based on the characteristics of tasks and hardware platforms and automatically selects the optimal execution environment and resource configuration. Dynamic metering and billing ensure accurate metering and standardized billing for the resource usage of combined clusters across management domains.

With the development of AI, computing power network construction technology will become more intelligent, automatically selecting the optimal combination of computing resources and allocation strategies based on factors such as task type, resource characteristics, and user demand. Future development will focus on data privacy protection, network security protection, and fault-tolerance mechanism design to ensure the stable operation of the computing resource network and security of user data. With the popularity of 5G technology and the development of edge computing, a computing power network for diverse computing will achieve closer integration with 5G networks and edge devices, and provide users with faster, real-time responsive computing services using their computing power and low-latency characteristics.

(4) Flexible intelligent tactile sensor

The tactile sensor, as a key support technology for robots, is a bridge that connects the external environment and robot body to imitate the tactile sensing ability of human skin and realize the robot's sensitive and accurate perception of the physical information of the external environment. Flexible intelligent tactile sensors combine flexible electronic technology and intelligent perception algorithms with measurement adaptability and contact information intelligence, thereby allowing robots to perform intelligent interaction and manipulation tasks on complex robot bodies and object surfaces in nonstructural environments.

At present, its main technical directions include ① flexible material and its manufacturing technology, ② perception mechanism and algorithm, ③ tactile sensing simulation, and ④ multimodal perception integration and application in manipulation.

First, new flexible polymers, nanomaterials, and biomaterials with good electrical and mechanical properties must be used to fabricate substrate, sensing layer, and electrode materials for flexible tactile sensors to enhance their flexibility, durability, and adaptability. In addition, generalized intelligent sensing methods have been developed to enable sensors to achieve sensitive and accurate sensing of multimodal parameters, such as contact force, shape, temperature, and position. To cope with the high cost of obtaining large-scale data for tactile sensors, it is critical to develop high-quality tactile sensing simulation platforms and the corresponding migration algorithms. Tacchi, a representative visual-based tactile sensor simulator, can provide rich tactile information and improve tactile learning efficiency. It also combines various flexible tactile sensing mechanisms and large neural networks to achieve multimodal sensory fusion of sensors, leading to a more comprehensive and in-depth understanding of the environment and providing more complete, diverse, and accurate tactile sensory feedback, which is then applied to sophisticated manipulation tasks and achieving the bioinspired process from tactile perception to operation.

(5) High-speed free-space optical communication technology

High-speed free-space optical communication technology uses laser beams as carriers for high-speed information transmission in free-space. Compared to traditional microwave communication, it has advantages such as high speed (up to 100 Gb/s), strong resistance to electromagnetic interference, and no spectrum restrictions. In addition, it has the benefits of a small terminal size, lightweight, low-power consumption, and easy deployment. Based on these features, high-speed free-space optical communication technology has significant strategic and practical applications in the military and civilian domains, including planetary exploration, lunar exploration, Earth observation, navigation reconnaissance, low-Earth-orbit mobile communication, and emergency rescue.

However, because of the long traveling distance of the laser in space, it is prone to divergence, and several factors, such as atmospheric absorption, refraction, background light interference, and cloud particle scattering, may adversely affect ground reception. Therefore, high-power light sources, high-spectral efficiency modulation, high-sensitivity interference-resistant optical signal reception, precise and reliable high gain antenna design, fast and accurate acquisition, pointing, and tracking technology, and dynamic and robust optical networking technology are just a few of the challenges that technology still faces in implementing a high-speed, stable, reliable, and cost effective optical space information networks.

In recent years, some countries have preliminarily acquired the capability of 100 Gb/s space laser communication because of the global deployment of space information networks and relentless exploration of high-power semiconductor lasers, precise optical filtering devices, highly sensitive optical detectors, and rapid, precise integrated optomechatronic technology. Currently, space optical communication technology is gradually shifting from a point-to-point mode to relay forwarding and the establishment of high-speed, intelligent, and integrated optical space information networks.

(6) Terahertz solid-state phased-array integrated circuit

Terahertz solid-state phased-array integrated circuit (IC) can steer the beam direction flexibly, implement fast tracking, and precisely detect targets in terahertz communication and radar imaging systems through highly integrated transceiver, switching, and amplitude-phase control devices, significantly reducing the system volume and cost. Terahertz waves are electromagnetic waves with a frequency range of 100 GHz to 10 THz. Their electromagnetic spectrum is between the microwave frequency band and the infrared spectrum, and is in a special position between the traditional electronics and photonics research frequency bands, with large communication transmission capacity, high resolution, good penetration, and excellent spectral characteristics. Because of the widespread installation of cellular communication and wireless sensing, the spectrum resources below 30 GHz are already crowded, and it is highly desirable to develop a spectrum resource in the terahertz band. However, because of the large propagation loss in the terahertz band and limited device power, it is necessary to use phased-array systems to provide high antenna gain and dynamic beam tracking. Therefore, terahertz solid-state phased-array ICs based on advanced compounds and silicon-based IC processes are the core technical solution of terahertz technology, and have become the focus of research in the emerging generation of wireless communication and high-precision terahertz radar systems.

In recent years, the cut-off operating frequency and device performance of silicon-based terahertz IC technology have increased rapidly because of the continuous improvement in compound- and silicon-based IC processes, particularly driven by Moore's law. Terahertz solid-state phased-array IC technology significantly improves the performance and reliability of terahertz systems by improving system integration and reducing the physical size of the system, while also reducing system cost and application technical requirements. Terahertz solid-state phased IC technology has become an important strategic direction in the field of electronic information. In 2021, the USA Defense Advanced Research Projects Agency (DARPA) launched the "G-band Array Electronics" (ELGAR) project, and China has also supported and financed similar research projects in this field. In the future, terahertz solid-state phased-array IC technology will be further developed for higher frequencies, higher integration, and better performance.

(7) Artificial-intelligence-based fault diagnosis and detection

AI-based fault diagnosis and detection processes data uses machine learning techniques (e.g., deep neural networks) to achieve fault detection, diagnosis, and prediction of test objects. In recent years, research on AI-based fault diagnosis and detection has received extensive attention globally. The main directions include: ① generalized intelligent fault diagnosis and detection, adaptability in complex environments, and transferability across different scenarios; ② interpretable intelligent fault diagnosis and detection, such as constructing interpretable network models and visualizing the semantic information embedded in features; ③ intelligent fault diagnosis and detection with weak data quality, such as exploring generative models for data complementation, and meta-learning-based diagnosis and detection algorithms; ④ information fusion-based intelligent fault diagnosis and detection, including data-, feature-, and decision-level fusion; ⑤ lightweight intelligent fault diagnosis and detection, such as deep neural network compression and intelligent models for edge and mobile devices.

Despite the plethora of AI-based fault diagnosis and detection methods, several key bottlenecks remain rarely addressed, including: ① significant data dependency and lack of mechanism analysis during data mining processes; ② insufficient research on boundaries and factors influencing model generalization; ③ lack of research on the mechanism and quantitative standards for interpretability; ④ credibility concerns underlying the deployment of AI models in risk-sensitive scenarios. Based on the aforementioned issues, accelerating the advancement of intelligent fault diagnosis and detection technology in areas such as technological innovation, engineering practices, and trustworthy safety will be an important direction for the future development of fault diagnosis and detection technology based on AI.

(8) Large-size silicon carbide materials and power chips

Large-size silicon carbide (SiC) materials are mainly SiC single-crystal substrates with a diameter of 6 inches (150 mm) or even larger. They are used to obtain high-quality epitaxial films for the fabrication of high-performance power chips. Large-scale deployment of semiconductor SiC materials and chips is emerging, targeting the goals of carbon peaking and carbon neutrality. As an IV-IV compound semiconductor material, SiC has a wide bandgap, high thermal conductivity, high breakdown field strength, high electron saturation drift rate, and excellent chemical and thermal stabilities. SiC is expected to be widely used in the field of power electronics related to renewable energy due to the fact that SiC power devices can work at higher temperature, higher breakdown voltage and faster switching speed, lower on-resistance, and better durability compared with silicon power devices.

For large-size SiC materials, the main direction of technological innovation is to increase the size and thickness of SiC single crystal and reduce the defect density of SiC single crystal, enabling lower-cost and higher-quality SiC substrates. The size of SiC single crystal has increased over the years. The mainstream SiC substrate size is now 6 inches. Research institutions and companies are competing to develop technologies for 8-inch SiC single crystal and substrates. The thickness of a SiC single crystal is typically in the range of 10–30 mm. There is still a long way to go in the development of meter-long SiC single-crystal-like silicon single crystal. For SiC single crystal volume defects, such as micropipes have been almost eliminated. However, the density of other defects, such as dislocations, remains high, generally on the order of magnitude of $10^3/cm^2$, which needs to be significantly reduced.

SiC diodes have been well developed. In contrast, the performance of SiC metal-oxide-semiconductor field effect transistors (MOSFETs) needs to be improved. First, the activation of implanted ions in the injection region of MOSFETs should be improved, which critically depends on ion implantation and subsequent high-temperature annealing during device fabrication. Second, optimizing the key parameters for thermal oxidation and annealing to reduce the density of interface defects and oxide defects is an important issue that should be addressed to enhance the electron mobility and gate-oxide reliability of MOSFETs. Finally, the reliability of MOSFETs must be significantly improved in terms of gate-oxide growth and post-annealing techniques, short-circuit robustness, anti-surge and anti-avalanche, and irradiation reinforcement.

(9) Naked eye 3D technology based on light-field technology

Naked eye three-dimensional (3D) technology based on light-field technology refers to a technology that uses light tracing to construct 3D objects by reproducing elements such as the luminous position in the all-light equation, two luminous angles of the direction of the observation position, wavelength of light λ, and the observation time t, thereby allowing users to directly see “3D objects in the real world” through their eyes. Compared with traditional naked eye 3D display technology, the light-field display increases the displacement parallax based on binocular parallax to have ultra-high information density and spatial bandwidth, providing the user with a retinal-level visual experience.

The concept of the light field was proposed in 1936, and it can be divided into two parts: light-field acquisition (imaging) and light-field display. Light-field acquisition includes camera arrays, microlens arrays, and pinhole imaging. The light-field display includes Magic Leap’s scanning type, multiprojection type, Stanford University’s multilayer screen technology, Ricoh’s multifocal surface, and integrated imaging technology implementation types. The scanning type uses a high-speed projector and a rotating directional scattering screen to produce a horizontal multiview; however, its equipment and site requirements are strict. The multiprojection type uses a projection array and a rotating/directional scattering screen to generate a horizontal multiview. Its equipment size and cost are limited. The multilayer screen type uses a multilayer LCD screen and directional backlight or ordinary backlight, with the algorithm to achieve a continuous depth-of-field. The current technical bottleneck is focused on algorithm research. A multifocal surface LCD screen or microdisplay with microlevel zoom lens design could achieve a continuous depth-of-field with the support of certain algorithms. In addition, the optimal combination between different algorithms is also the most concerned research content for this field, in order to achieve an ideal continuous depth-of-field finally. Integrated imaging uses a panel and lens array to achieve a continuous depth-of-field, and a light-field camera to obtain the video source and then reproduce it by the array lens.

By using light-field display technology to reconstruct the light-field distribution of 3D objects in space, a 3D display effect that is close to the natural world can be realized. Therefore, in the future, naked eye 3D technology based on light-field display will be an important information interaction mode. Ultra-high resolution display panels, which benefit from the continuous development of semiconductor display technology, expand the possibilities for optical field naked eye 3D display technology. Combined with eye tracking and motion capture, intelligent interaction under pupillary-level dense viewing points will be realized gradually.

The advancement of display technology will promote the advancement of the entire industrial chain, including display chips, high-resolution panel materials, 3D content, and the development of upstream and downstream ecological linkages. With the gradual improvement of the industrial chain, the naked eye 3D display based on light-field technology will soon achieve industrial application breakthroughs in medical imaging, detection, and minimally invasive surgery. Additionally, it will enable electronic industry design automation, online education model innovation, commercial exhibition display, culture, and entertainment.

(10) Augmented reality space operating system

The augmented reality space operating system is a 3D operating system designed for extended reality (XR) devices that enable the interplay of virtual and real-time interactions and realistic presentations. The primary objective is to weave a virtual space into the fabric of the real world using spatial perception technology. It supports 3D multimodal user interactions via recognition algorithms, such as eye tracking and gestures, to construct a spatial application system that enables natural interactions, thereby realizing multichannel, natural interactive operations within an immersive virtual-reality fusion space. Unlike traditional PC and mobile operating systems, the augmented reality space operating system underscores the user's immersive experience in 3D space. This enables users to append virtual objects to the physical world, thereby enriching the blend of virtual and real presentations and interactions. The spatial operating system, compared to screen interfaces, promotes more natural and intuitive operations and interactions, forming the cornerstone of the meta-universe application ecosystem.

The research directions include the followings. ① Spatial application system: We should construct and manage spatial applications running on XR devices by leveraging the high-performance 3D rendering engine at the system level. This involves defining a new 3D application system and exploring the most effective ways to design, render, and use 3D applications in space. ② Spatial interaction system: Based on a human-centered design concept, we should research and develop a natural, intuitive, and efficient user interaction mode based on the multimodal interactions of multiple recognition algorithms. ③ Spatial perception fusion: We should develop efficient algorithms for spatial positioning, tracking, and environmental understanding, enabling XR devices to better perceive their environment and achieve the seamless integration of virtual content and physical space.

In the future, the augmented reality space operating system may revolutionize the traditional operating system model with a new spatial application system. Innovative interaction methods, such as eye tracking and gestures, can provide a more realistic and natural human-machine interface, spatial understanding, perception capabilities, and stronger interactive applications. The final goal is to achieve efficient acquisition and processing of hybrid and enhanced intelligent information, resulting in experiences that transcend the real space.

2.2 Interpretations for three key engineering development fronts

2.2.1 Light-controlled phased-array technology

Since the 1890s, phased-array technology has been widely used in wireless communication, remote sensing, security checks, medical instruments, and imaging systems for both defense and civil applications. As the 21st century witnessed the rapid growth of the big data market due to the development of 5G/6G mobile networks, IoT, and AI, "optical transmission" started to replace "electrical transmission" to achieve higher data transmission rates, from which the development of light-modulator, light-switches, and optical waveguides greatly benefit the application of "optical-modulation concept" in microwave phased arrays to cater for the demand of low-cost high-performance phased arrays, such as the aforementioned MPPA and OTMPA.

MPPA focuses on the wideband low-cost transmission of phased microwave signal using light as the carrier, thereby improving the scanning range and bandwidth of phased arrays by greatly reducing the heat emission and transmission loss caused by large-scale microwave feeding networks and TR modules in conventional phased arrays. Meanwhile, MPPA is advantageous in its native anti-radiation characteristic because of the different frequencies used for transmitting/receiving and wave guiding, which is particularly useful in space applications. A recent technological trend is the development of highly integrated on-chip microwave-photonic modulators with higher precision, dynamic range, scale time delay, and resolution to improve the scanning ability of phased arrays. Representative research institutes in this technology include Zhejiang University, Tsinghua University, University of Electronic Science and Technology of China, China Electronics Technology Group Corporation, University of Ottawa, University College London, USA Naval Research Laboratory, University of Virginia, University of California, and Osaka University.

OTMPA focuses on the use of light-sensitive materials or components to tune the amplitude/phase distribution over the antenna aperture and waveguide structures through controllable light rather than a conductive medium such as conductive wires, which significantly reduces the ohmic loss and surface-wave loss caused by massive complex passive microwave feeding networks and the power loss caused by conventional active-phase shifters. Consequently, the optical-tuning microwave radiation principle offers higher gain (owing to scalability), antenna efficiency (owing to simpler feeding), operating frequency (owing to lower ohmic loss of wave-guiding structures), and degrees of freedom in polarization (owing to wireless optical tuning). Representative research institutes in this technology include: ① Australian National University, which first proposed the concept and validation of light-controlled metamaterials in 2012 by combining photonic diodes and varactors; ② USA Naval Research Laboratory, which patented the use of light-sensitive films for 1-bit optically tuned reflectarray antennas in 2020; ③ Southeast University and Xidian University, which combine photon cells and varactors/phototon-resistors for optically tuned reflective metasurfaces of continuous phase tuning in the C-band in 2020/2022; ④ ShanghaiTech University, which first proposed the combination of photon resistors and PIN diodes for optically tuned reflectarray antennas of 1024 elements and ±60° scanning range without grating lobes in the X-band in 2022, represents the latest progress in this field.

Tables 2.2.1 and 2.2.2 summarize global patent applications and publications by different countries and institutes, respectively. China outperformed all the listed countries in terms of the number of patents, although it ranked fifth in terms of citations per patent. Conversely, the USA is ranked second in the number and citations of patents, showing higher quality and value of the patents on average than China. Although the UK and Canada show a high citation per patent, the total number is much smaller than that in China and the USA. Therefore, China and the USA led the research and development of light-controlled phased-array technology, followed by Japan and Republic of Korea. In terms of institutions, the top three Chinese institutes that filed the largest number of patents included Zhejiang University, China Electronics Technology Group Corporation, and Space Star Technology Co., Ltd; however, the Analog Photonics Limited Liability Company had the highest citation rate, indicating better technology transfer and industrialization. The important strategic value of this technology to a country, particularly in the area of aerospace, is immediately seen by a simple glance at the name of the institutes, which may be the reason that little inter-country cooperation has occurred except between China and Canada.

In the future, light-controlled phase array technology may have to address new market-driven challenges, such as frequency-spectrum sparsity, increasing working frequency, increasing intelligence and bandwidth, higher integrity at lower cost, and decreasing footprint. The roadmap of the engineering development front of "light-controlled phased-array technology" is shown in Figure 2.2.2.

For MPPA, to meet the requirements of ① lower power consumption of optical network for beamforming, ② improved accuracy of optical time delay, ③ higher space continuity, coverage, and space-time resolution, ④ reduced frequency-conversion loss in scalable systems, and ⑤ high signal-to-noise ratio (SNR) and high gain transmission at low-power laser carrier, the forefront research topics mainly focus on ① the compact and low-power integration of functional components, ② the exploration and development of new optical-electrical converting mechanism and devices, ③ the development of high-precision and high

Table 2.2.1 Countries with the greatest output of core patents on "light-controlled phased-array technology"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	184	70.77	529	49.76	2.88
2	USA	43	16.54	426	40.08	9.91
3	Republic of Korea	13	5.00	57	5.36	4.38
4	Japan	10	3.85	3	0.28	0.30
5	Russia	4	1.54	3	0.28	0.75
6	UK	2	0.77	42	3.95	21.00
7	Canada	1	0.38	8	0.75	8.00
8	Germany	1	0.38	0	0.00	0.00
9	Israel	1	0.38	0	0.00	0.00
10	India	1	0.38	0	0.00	0.00

Table 2.2.2 Institutions with the greatest output of core patents on "light-controlled phased-array technology"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Zhejiang University	12	4.62	55	5.17	4.58
2	China Electronics Technology Group Corporation	12	4.62	22	2.07	1.83
3	Analog Photonics Limited Liability Company	9	3.46	129	12.14	14.33
4	Space Star Technology Company Limited	9	3.46	26	2.45	2.89
5	Korea Advanced Institute of Science and Technology	6	2.31	29	2.73	4.83
6	Jilin University	6	2.31	14	1.32	2.33
7	Changchun University of Science and Technology	5	1.92	39	3.67	7.80
8	Tsinghua University	5	1.92	34	3.20	6.80
9	National University of Defense Technology	5	1.92	5	0.47	1.00
10	Quanergy Systems Incorporated	4	1.54	33	3.10	8.25

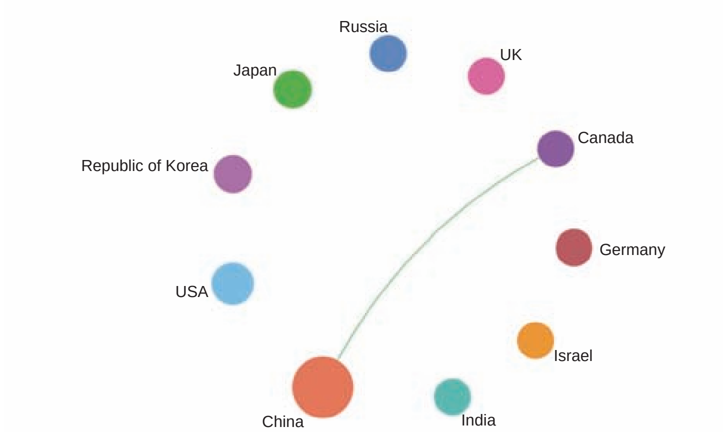

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "light-controlled phased-array technology"

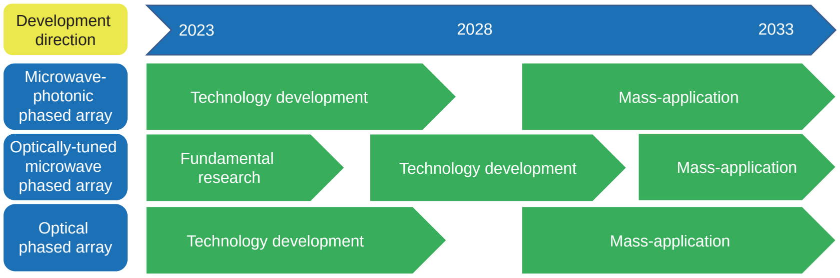

Figure 2.2.2 Roadmap of the engineering development front of "light-controlled phased-array technology"

resolution optical-delay components, and ④ the development of low-complexity low-cost and low-power microwave-photonic transmission link or waveguides.

There are still many original innovative findings and research pending development for the cutting-edge technology of OTMPA, which emerged in the early 2020s, such as ① increasing the speed and working frequency of optically microwave switches, ② exploring new mechanisms and methods for light-induced microwave tuning, ③ improving the resolution and continuity of optically controlled microwave-aperture tuning, ④ increasing the contrast ratio of light-sensitive materials and components, and ⑤ exploring the application of the new technology in multiple contexts of various applications including wireless communication, remote sensing, data storage, and over-the-air computing in different electromagnetic environment and platforms.

Finally, the research topics for optical phased arrays mainly focus on the development of high performance optical delay and modulators for compact, low-cost, low-power optical beamforming with high efficiency and a large field of view. Different types of optical modulators include ① heat-light modulation for refractive-beam steering by heat-controlled refraction-changing optical waveguides, ② mechanical-light modulations for reflective-beam steering by rotational micromirrors, ③ electric-light modulations for refractive-beam steering by light-induced property-changing materials, ④ liquid-crystal-light modulations for refractive-beam steering by voltage-controlled polarization and refraction of liquid crystals, and ⑤ phase-changing-light modulations for refractive-beam steering by phase-changing materials. The various light-modulating mechanisms can be further leveraged to develop innovative components and devices such as ① wavelength-tunable integrated laser emitter of compact size, low cost, high power, high speed, high stability against temperature, ② stacked-lens-based light-splitter with high consistency, yield rate, and low cost, ③ high performance light-phase-modulators of scalability, high power, high stability, low loss, low cost, and low noise, and ④ an optical-antenna-array with a large scanning range, high modulation efficiency, compact integration, high space-time resolution, and high antenna efficiency.

In summary, light-controlled phased arrays have the advantages of low cost, high performance, and lower dependence on precision-fabrication for numerous applications, including but not limited to wireless backhaul microwave communication, cellular communication, space-terrestrial networks, space-light communication, autonomous driving, radar sensing and detection, and biomedical health. Specifically, OTMPA may find extensive and promising applications in low-Earth-orbit communication owing to their advantages of low cost, large bandwidth, high efficiency, and anti-interference characteristics over the coming 5–10 years. OTMPA can be readily adapted to reconfigurable intelligent surfaces for smart relay communication in the next generation of wireless networks.

2.2.2 Control technology of unmanned systems based on brain–computer interface

In recent years, the rapid advancement of AI technology has accelerated the development of unmanned systems toward intelligence. However, when faced with various unexpected and abnormal situations, AI-based unmanned systems often fall short of expectations. Integrating "brain" and "machine" intelligence to fully leverage the advantages of these two forms of intelligence is an important direction for achieving intelligent unmanned systems. The development of BCI technology enabled the fusion of “brain” and “machine” intelligence.

The concept of BCI was first proposed by Jacques Vidal in 1970. It mainly refers to the use of brain signals in human–computer interactions to control computers or external devices. For a long time, the accuracy and reliability of decoding brain intentions were relatively low because of limitations in software and hardware conditions that could not meet the control requirements of unmanned systems. With the recent advancement of BCI technology, not only has it higher accuracy in recognizing active brain intentions, also passive monitoring of specific brain states. As a result, researchers have begun to combine BCI technology with unmanned system. Using specific experimental paradigms, such as event-related potentials, steady-state visual evoked potentials, or motor imagery, accurate extraction of subjective intentions from subjects can be achieved through BCI technology to realize process control of unmanned systems. However, this process control method is highly inefficient because of the low information transfer rate of BCI. To address this issue, researchers transformed the recognition results of the BCI into predefined specific instructions. Unmanned systems independently perform a specific series of actions based on these instructions to achieve brain–machine collaborative control for multitasking. This improvement greatly enhances the control efficiency of unmanned systems. However, the brain and machine are still two independent control systems and do not constitute a unified decision making and control system. Recently, researchers have found that better task performance can be achieved by fusing the brain and machine through decision or feature layers in tasks, such as target recognition and path planning for unmanned systems. This transformation has shifted the BCI-based unmanned system technology from unidirectional control to bidirectional interaction and integration of the brain and machine. In the future, BCI technology will not only provide commands or instructions for unmanned systems, but will also be deeply integrated into daily tasks such as target recognition, path planning, and task management in unmanned systems to achieve true human–computer fusion and intelligent enhancement.

Table 2.2.3 shows the distribution of patent outputs at the forefront of engineering development for BCI-based unmanned system technology. China has an obvious advantage in that ranks first in both patent quantity and citation frequency globally. The number of patents in China is approximately 15 times that in the second-ranked USA, but the average citation frequency is lower than that in the USA. Germany is China’s main international cooperation partner, while India is the main international cooperation partner for the USA; other countries conduct independent research (Figure 2.2.3). Among the Top 10 patent-producing institutions (Table 2.2.4), Beijing Institute of Technology and Academy of Military Medical Sciences affiliated with the Chinese People’s Liberation Army produced the most patents, but only by a small margin compared with the other eight institutions. In terms of average citation frequency, Southeast University ranks the highest, followed by Shanghai University, Tianjin University, and Beijing Institute of Technology; their data are similar. Furthermore, all the Top 10 institutions are from China, demonstrating China’s high level of attention and strong research and development capabilities in this field.

Figure 2.2.4 shows the development direction of the control technology of the unmanned system based on brain–computer interfaces. In the future, portable, high-SNR, and high-throughput EEG signal acquisition equipment will enable more accurate decoding of brain functions, including functional near-infrared spectroscopy, and eye movement information, because of the development of brain–computer interface technology. Multimodal physiological signals are expected to be integrated to achieve synchronous acquisition, which will enhance the reliability of brain–computer interfaces. Consequently, brain–computer control methods will progress from discrete control methods with low degrees of freedom to continuous control methods with high degrees of freedom. At this stage, the intelligence of the unmanned system will progress from a simple combination of the brain and computer to a hybrid intelligence of brain–computer fusion. This marks a deep integration of the brain and machine at the decision-making level, expanding unmanned systems to respond to unknown and unexpected situations and effectively handle emergencies. As the brain–computer interface and AI technology continue to develop and integrate further, the brain–computer control method will develop into task-level control. During this phase, the unmanned system itself becomes more intelligent, and the brain is responsible for higher-level cognitive decision-making tasks. At this stage, “brain” and “machine” will be deeply integrated at the information layer, and the two-way information perception and decision-making fusion will eventually form an integrated intelligent system, which is characterized by the synergistic effect of “brain” and “machine,” enabling them to jointly solve problems and expand cognitive abilities. Ultimately, this advancement will enable unmanned

Table 2.2.3 Countries with the greatest output of core patents on “control technology of unmanned systems based on brain–computer interface”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	370	79.74	1 047	77.90	2.83
2	USA	25	5.39	129	9.60	5.16
3	Republic of Korea	20	4.31	64	4.76	3.20
4	India	19	4.09	12	0.89	0.63
5	Japan	11	2.37	24	1.79	2.18
6	Germany	5	1.08	10	0.74	2.00
7	France	4	0.86	23	1.71	5.75
8	Barbados	2	0.43	27	2.01	13.50
9	Russia	2	0.43	4	0.30	2.00
10	Brazil	2	0.43	0	0.00	0.00

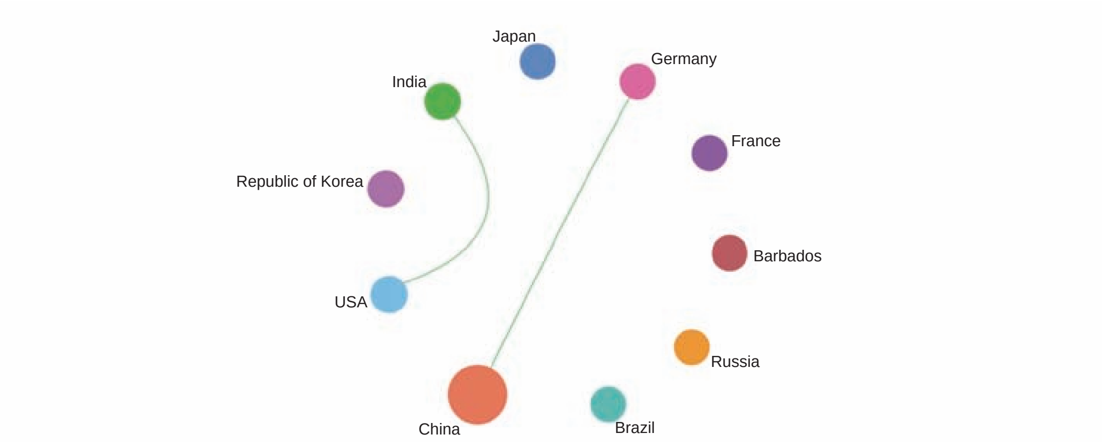

Figure 2.2.3 Collaboration network among major countries in the engineering development front of “control technology of unmanned systems based on brain–computer interface”

Table 2.2.4 Institutions with the greatest output of core patents on “control technology of unmanned systems based on brain–computer interface”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Beijing Institute of Technology	8	1.72	51	3.79	6.38
2	Academy of Military Medical Sciences, PLA Academy of Military Science	8	1.72	25	1.86	3.12
3	Tianjin University	7	1.51	45	3.35	6.43
4	Northwestern Polytechnical University	7	1.51	19	1.41	2.71
5	Shanghai University	6	1.29	39	2.90	6.50
6	Beihang University	6	1.29	30	2.23	5.00
7	Xi’an Jiaotong University	6	1.29	27	2.01	4.50
8	Southeast University	5	1.08	38	2.83	7.60
9	Zhejiang University	5	1.08	20	1.49	4.00
10	Beijing University of Posts and Telecommunications	5	1.08	9	0.67	1.80

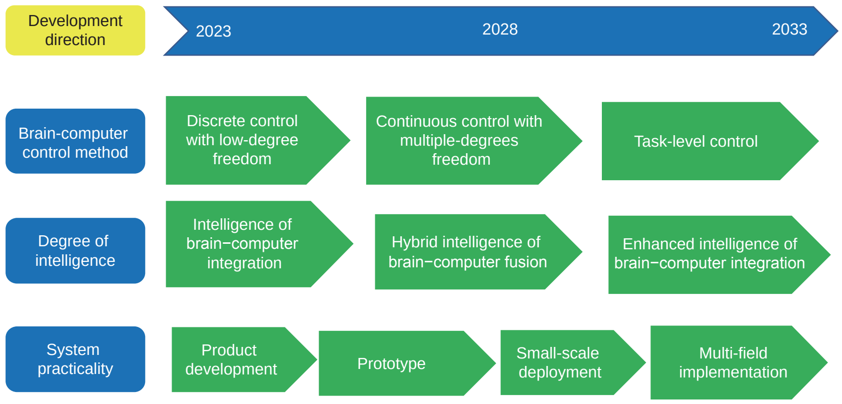

Figure 2.2.4 Roadmap of the engineering development front of “control technology of unmanned systems based on brain–computer interface”

systems to handle complex problems better and complete difficult tasks. From a practical standpoint, the current unmanned system technology based on brain–computer interfaces has undergone initial principle verification and entered the product research and development stage. It is expected that within 10 years, it will progress from principle prototypes to small-scale applications and eventually reach the multifield promotion and application stage. Brain–computer fusion is an inevitable trend in the development of unmanned systems based on brain–computer interfaces. The integration of “brain” and “machine” dual intelligence can bring many innovations and applications, and is expected to be used in traffic safety, aerospace, navigation, assistance for the elderly and disabled, medical assistance, rescue and disaster relief, industrial control, and other fields to produce more positive impacts.

2.2.3 Computing power network construction technology for diverse computing

With the rapid development of big data and AI technology, the demand for computing power and storage capacity in various industries is increasing. The main goal of computing power network construction technology for diverse computing is to build a computing power network that can meet the needs of heterogeneous computing to improve computational efficiency, reduce energy consumption, and solve the problems of insufficient computing and resources encountered by the traditional computing model when dealing with large-scale data and complex tasks. Computing power network construction technology for diverse computing can combine various computing resources to form a powerful computing power network that can better meet the computational needs of different application scenarios and realize efficient data computation and processing.

Computing power network construction technology for diverse computing has broad application prospects because it can integrate and optimize computing resources to achieve efficient computing capabilities. Governments worldwide are implementing several important plans for resource sharing between computing and data centers, and they have made some progress. The U.S. government has launched XSEDE, a federal program for sharing high performance computing and data resources to connect multiple high performance computing centers through a network to provide researchers and engineers with various computing and data resources. The European Union promoted the European Supercomputer Program (EuroHPC) to establish a Europe-wide supercomputing network to provide European research institutions and industry access to high performance computing resources through the PRACE supercomputer consortium. In addition, technology giants such as Google, Microsoft, and Amazon have launched their respective distributed cloud services or distributed computing engines to realize the cross-regional sharing and scheduling of large-scale resources. In the research field, the Lawrence Berkeley National Laboratory and Los Alamos National Laboratory in the USA have explored and experimented with large-scale scientific data sharing and the application of a unified runtime framework.

In China, research in this area is mainly conducted by scientific research institutions, universities, and telecommunication operators. In the context of the construction of channel computing resources from east to west and the Supercomputing Internet, the Computer Network Center of the Chinese Academy of Sciences has taken the lead in building a national high performance computing environment, effectively integrating high performance computing resources, and providing high performance computing services through a unified access portal. Emerging computing sharing platforms, such as the Integrated Computing Power Network of Shandong Province and China Smart computing power network led by Jinan Supercomputing and Peng Cheng Laboratory, are also developing, effectively promoting the interconnection and synergy of computing, data, software, and other resources in various provinces and municipalities.

Globally, several countries and regions are conducting research in this field. As shown in Tables 2.2.5 and 2.2.6, the USA is the country with the largest patent output in this field, accounting for 74.45%, indicating that the USA is a world leader in computing power network construction technology for diverse computing, with representative organizations such as U.S.-based EMC IP Holdings and International Business Machines Corporation. China has the second-largest patent output, accounting for 17.71%.

Computing power network construction technology for diverse computing usually requires close cooperation among multiple institutions and enterprises to achieve data sharing, technology synergy, and resource optimization. There is little cooperation among institutions and enterprises globally (Figure 2.2.5), and only the USA and India have cooperated, and the cooperation network among institutions has yet to be formed. Therefore, there is an urgent need to create cooperation network among countries and institutions to promote the development and application of this technology through joint scientific research, technology exchange, and project cooperation.

As shown in Figure 2.2.6, computing power network construction technology for diverse computing has the following key development directions in the next 5–10 years.

1) Computing power network architecture optimization: Perform computing power network architecture design and topology optimization based on Y.2501 computing power network framework. Better scheduling and management of computing resources will improve computing power and performance by establishing a more flexible and efficient basic communication network structure.

2) Heterogeneous resource convergence: In computing power networks, the convergence of different types of computing resources, such as central processing units, graphics processing units, and field-programmable gate arrays, will continue to evolve in-depth. Computing power networks will better use these heterogeneous resources to provide more efficient computing capabilities as computing resource innovations and performance improvements continue. For example, more powerful and efficient gas pedals, new server architectures, and processor designs have emerged to drive the development of computing power networks.

3) Cross-domain resource management and task collaboration: The goal of cross-domain resource management and task collaboration is to achieve the efficient use of computing resources and high performance in task execution. Computing power networks can make full use of computational resources from different domains through cross-domain resource management and task collaboration, improve resource utilization and performance, and collaborate in the execution of multiple tasks simultaneously to achieve more efficient computation and data processing. This is critical for promoting the development and application of diverse computing.

4) Computing operation and trading: computing trading is an important means of realizing spontaneous market regulation in the computing power network system and coordinating the benefits of each service subject. To realize reasonable billing, it is necessary to establish a spatiotemporal model of resource use through multidimensional and multigranular information collection of computing resource usage and load indicators to realize reasonable billing.

5) Convergence of AI and computing power network: The rapid development of AI technology will converge with computing power network to provide more powerful intelligence and learning capabilities for computing tasks. The computing power network will realize intelligent resource management and automated decision making by integrating AI algorithms and technologies,

Table 2.2.5 Countries with the greatest output of core patents on "computing power network construction technology for diverse computing"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	475	74.45	2 476	81.61	5.21
2	China	113	17.71	328	10.81	2.90
3	Germany	9	1.41	11	0.36	1.22
4	Canada	7	1.10	24	0.79	3.43
5	Russia	7	1.10	22	0.73	3.14
6	UK	7	1.10	8	0.26	1.14
7	India	5	0.78	5	0.16	1.00
8	Netherlands	4	0.63	0	0.00	0.00
9	Japan	2	0.31	4	0.13	2.00
10	Ireland	1	0.16	147	4.85	147.00

Table 2.2.6 Institutions with the greatest output of core patents on "computing power network construction technology for diverse computing"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	EMC IP Holding Company	67	10.50	168	5.54	2.51
2	International Business Machines Corporation	43	6.74	208	6.86	4.84
3	Bank of America Corporation	41	6.43	142	4.68	3.46
4	Nuance Communications Incorporated	25	3.92	110	3.63	4.40
5	ReliaQuest Holdings Limited Liability Company	18	2.82	26	0.86	1.44
6	Microsoft Technology Licensing Limited Liability Company	15	2.35	49	1.62	3.27
7	Gamalon Incorporated	11	1.72	49	1.62	4.45
8	Intel Corporation	10	1.57	12	0.40	1.20
9	Beijing University of Posts and Telecommunications	9	1.41	53	1.75	5.89
10	Shandong Inspur Science and Technology Academy Company Limited	9	1.41	1	0.03	0.11

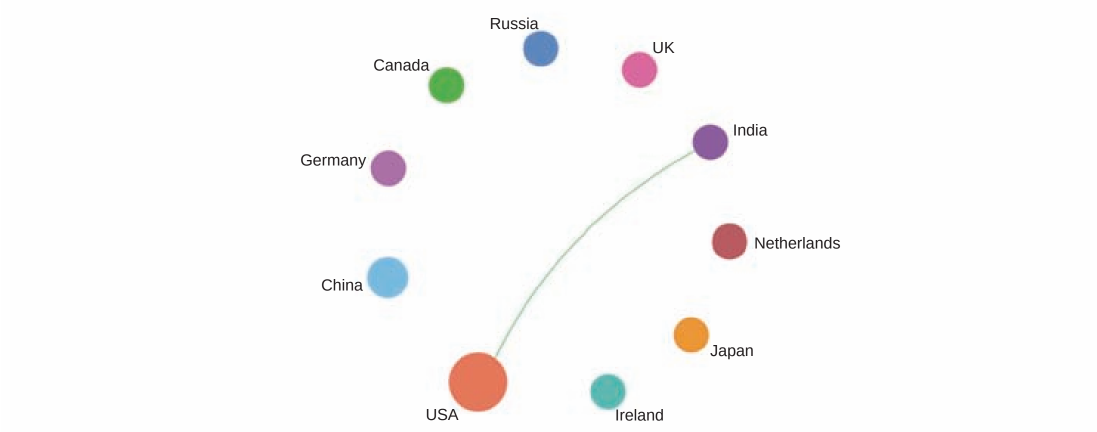

Figure 2.2.5 Collaboration network among major countries in the engineering development front of "computing power network construction technology for diverse computing"

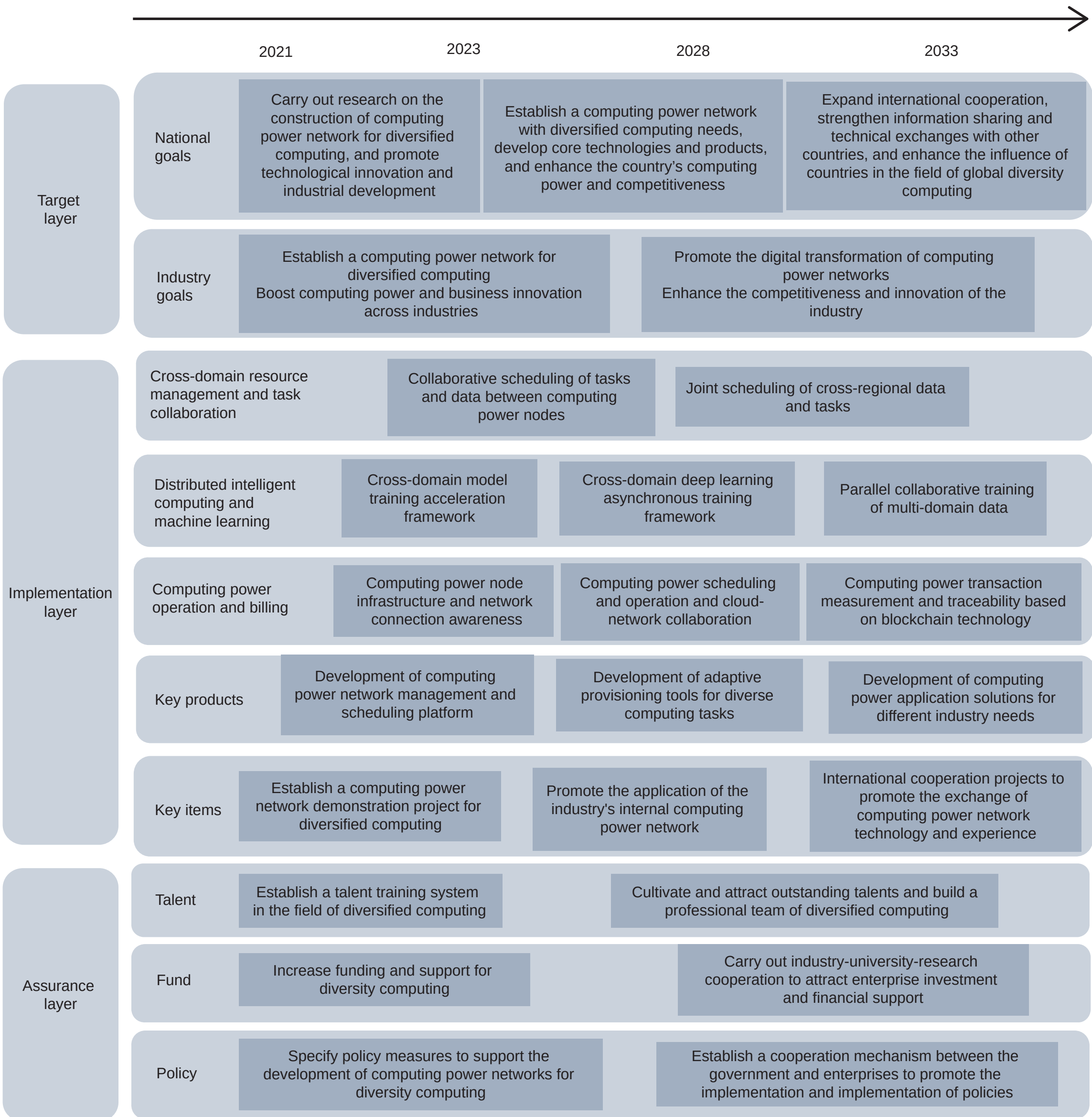

Figure 2.2.6 Roadmap of the engineering development front of “computing power network construction technology for diverse computing”

such as deep learning, machine learning, and natural language processing, to provide more intelligent and adaptive computing capabilities.

6) Enhancement of security and privacy protection technologies: With the use of large-scale data and the distribution of computing resources, protecting data security and privacy will become an important concern in the development of computing power networks. Future computing power networks will enhance security techniques, such as data encryption, access control, and authentication, to ensure the security of computational tasks and data, and the protection of privacy.

In the future, computing power network construction technology for diverse computing will gradually become the core technology for data processing and analysis in various fields and will be widely used in cloud computing, big data analysis, AI, IoT, and other fields to promote the development and innovation of these fields. In addition, this technology has great development potential to provide more efficient and intelligent solutions for public safety, smart cities, medical health, industrial manufacturing, and other fields.

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III. Chemical, Metallurgical, and Materials Engineering

1 Engineering research fronts

1.1 Trends in Top 11 engineering research fronts

The Top 11 engineering research fronts as assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Tables 1.1.1 and 1.1.2. "Design and process optimization of low-carbon and energy-saving metallurgical reactors", "integrated monolithic electrodes for highly efficient electrochemical energy storage", and "efficient preparation and catalytic mechanism of super-dispersed single-atom alloy catalysts" were recommended by experts directly. The other fronts were chosen by a panel of experts using core-paper statistics provided by Clarivate. Topics on "electrocatalysis, monoatomic catalysis and intrinsically safe battery" are still hot topics, with more than 200.00 citations per paper (Table 1.1.1). However, the annual number of core papers for all topics is decreasing (Table 1.1.2).

(1) Renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials

Biological carbon dioxide (CO_2) sequestration, which is a clean and highly efficient technique, is indispensable for realizing carbon peak and carbon neutrality goals. Renewable energy-driven bioconversion of CO_2 takes full advantage of biological CO_2 sequestration. In this technique, renewable energy, such as light or electricity, is used as a substitute for chemical energy to provide energy and reducing equivalents for biological carbon sequestration pathways that produce chemicals, fuels, and materials. To date, relevant research has focused on *in vitro* multi-enzyme-based CO_2 sequestration and whole cell-based CO_2 sequestration

Table 1.1.1 Top 11 engineering research fronts in chemical, metallurgical, and materials engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials	92	13 644	148.30	2018.9
2	Chaotic nonlinear enhancement technology of metallurgical flow field	120	9 337	77.81	2018.9
3	High-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization	107	25 965	242.66	2018.8
4	*In situ* molecular/atomic scale characterization of heterogeneous catalysts under reaction conditions	76	9 481	124.75	2018.7
5	Design and process optimization of low-carbon and energy-saving metallurgical reactors	82	3 788	46.20	2018.5
6	Rational design and fabrication of special alloys for cryogenic environments	148	13 642	92.18	2018.7
7	Integrated monolithic electrodes for highly efficient electrochemical energy storage	109	14 356	131.71	2018.4
8	Research on high-strength high-toughness and low-density steel	59	3 246	55.02	2018.4
9	Efficient preparation and catalytic mechanism of super-dispersed single-atom alloy catalysts	61	13 127	215.20	2019.0
10	Selective confined mass transport membrane for ion separation	81	9 394	115.98	2019.0
11	Intrinsically safe battery systems for renewable energy storage	131	31 898	243.50	2018.6

Table 1.1.2 Annual number of core papers published for each of the Top 11 engineering research fronts in chemical, metallurgical, and materials engineering

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials	16	21	26	17	12	0
2	Chaotic nonlinear enhancement technology of metallurgical flow field	26	25	30	21	15	3
3	High-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization	20	26	29	22	8	2
4	*In situ* molecular/atomic scale characterization of heterogeneous catalysts under reaction conditions	20	18	17	12	6	3
5	Design and process optimization of low-carbon and energy-saving metallurgical reactors	23	28	13	9	7	2
6	Rational design and fabrication of special alloys for cryogenic environments	43	25	37	23	16	4
7	Integrated monolithic electrodes for highly efficient electrochemical energy storage	37	21	28	16	7	0
8	Research on high-strength high-toughness and low-density steel	23	10	13	6	7	0
9	Efficient preparation and catalytic mechanism of super-dispersed single-atom alloy catalysts	8	13	17	14	9	0
10	Selective confined mass transport membrane for ion separation	10	20	22	22	6	1
11	Intrinsically safe battery systems for renewable energy storage	33	32	30	28	8	0

driven by light/electricity. The main goals have been ① the construction of new biological carbon sequestration pathways, ② the design and preparation of new biocompatible photo- or electrocatalytic materials, and ③ the adaptation of biocatalytic modules and photocatalytic modules. Bioconversion of CO_2 driven by renewable energy is a green process with a green raw material and green product. However, the overall energy efficiency of this technology is unsatisfactory, and there are still some bottlenecks in industrial applications. For future advances, the following directions are suggested: *in situ* characterization techniques for clarification of energy exchange mechanisms between biocatalysts and artificial catalysts to deepen the understanding of the coupling processes; core technologies for the rational design of enzymes and microbial cell factories to produce high-quality biocatalysts with high efficiency and adaptability and to further increase productivity; and advanced reactors and separation media to establish an integrated equipment and technology system for raw material supply, process intensification, and product separation engineering.

(2) Chaotic nonlinear enhancement technology of metallurgical flow field

In metallurgical processes, the interplay of flow, heat/mass transfer, and reaction involves intricate nonlinear dynamic mechanisms and multi-scale spatiotemporal characteristics. These features pose formidable challenges for the design, optimization, and operation of metallurgical reactors. Chaotic nonlinear enhancement of metallurgical flow field integrates knowledge from fluid dynamics, chaos theory, and nonlinear science. This aims to uncover the coupling and scale-up theory governing the interplay of flow, heat/mass transfer, and reaction in metallurgical reactor processes. Inherent connections between chaotic characteristics of the fluid phase, destabilization of intermediate steady flow structures, and enhancement through chemical chaos are elucidated. By constructing a correlation model between chaotic flow and temperature field-flow uniformity, the relationship between chaotic flow and temperature field-flow uniformity is precisely delineated. Leveraging the coupling mechanism between chaotic mixing characteristics, field uniformity, and the formation, transport, and conversion of multi-scale flow structures, this technology enhances heat and mass transfer efficiency by modulating the chaotic behavior of bubble clusters. This technique offers a fresh regulatory approach for topological coupling of complex multiphase flow patterns in metallurgical furnaces, and effectively addresses the challenge of accurately describing the cooperative nature of the flow field-temperature field during the enhancement process and intensified heat transfer via bubble cluster agitation. This theory is promising for further development of extreme and unconventional metallurgy, large-scale equipment, and intelligent metallurgy.

(3) High-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization

In the overall energy and environmental system, green and efficient conversion and utilization of CO_2 is important for realizing efficient conversion of low-carbon energy. Among the available methods, CO_2 capture, utilization, and storage technology has gradually become the key technology to cope with climate change and achieve the goals of carbon peak and carbon neutrality. Currently, green electricity provided by renewable energy sources such as solar energy and wind energy drives the catalytic conversion of CO_2. This solves the problem of excessive CO_2 emissions and realizes the direct conversion of intermittent electric energy into chemical energy, which is important for achieving carbon balance and optimizing energy consumption. The research on CO_2 electrocatalytic conversion has focused on the following aspects: ① the use of *in situ* spectroscopy to monitor key intermediates in the CO_2 reduction reaction (CO_2RR), and construction of the reaction network in the catalytic conversion process of CO_2 using theoretical calculations; ② design and development of high-performance electrocatalysts, regulation and optimization of the catalyst structure, and study of the structure–activity relationship between the catalyst and CO_2RR performance; and ③ design and optimization of the electrode structure and adjustment of the entire electrolytic reactor to control the operation of the reaction system and use its modular characteristics to achieve regulation and optimization so that each index meets the requirements of industrial application. Further development of CO_2RR requires improvement of the long-term continuous operation stability of the electrocatalyst and expansion of the scale of the CO_2 electrolyzer. Additionally, the target for practical application, the economics of the product, market supply, and demand need to be determined. The final product separation and recovery costs of excess CO_2 feedstock gas and electrolyte also require further design management.

(4) *In situ* molecular/atomic scale characterization of heterogeneous catalysts under reaction conditions

The structure and surface/interface properties of a catalyst are directly related to the catalytic performance and provide direct evidence for modeling. The active sites of catalysts and coordination environment change dynamically during catalytic reactions, and their spatiotemporal evolution provides vital information for the rational design of heterogeneous catalysts. The characterization of these surface/interface structures and chemistry, especially *in situ* characterizations under relevant reaction conditions, is important for elucidating the mechanisms. State-of-the-art *in situ* characterization techniques for heterogeneous catalysts at the molecular/atomic scale under various reaction conditions include *in situ* electron/scanning probe microscopy, *in situ* infrared/Raman spectroscopy, and X-ray photoelectron/absorption spectroscopy. Research has focused on ① revealing the structural active sites of specific reactions through *in situ* atomic-scale observation of dynamic structure changes of heterogeneous catalysts for rational design of atom-precise new catalysts; ② revealing the chemisorption and dissociation of molecules at the catalyst surface and determining the intermediates and their spatiotemporal distributions to elucidate the entire reaction route; and ③ combining multiple characterization methods and model catalysts to relate structural and chemical active sites for critical chemical reactions.

(5) Design and process optimization of low-carbon and energy-saving metallurgical reactors

In the process of size amplification, structure adjustment, and process optimization of super-large or special smelting equipment, a lack of a theoretical basis often leads to equipment amplification distortion, operation instability under changeable working conditions, and amplification mismatch between the theoretical model and practical equipment. This can lead to high energy consumption of the metallurgical reactor and smelting process. The operation process involves complex concentration-melt-rich oxygen jets, electric–magnetic–flow–heat–particles–components multi-fields, cooperative coupling between microscopic response, mesoscopic motion, and macroscopic operation, and requires size amplification in the design of low carbon smelting equipment and fine optimization for processes of dynamic test and simulation methods. Future research should focus on developing new methods for quantitative visual characterization of the flow field in a cold simulated multiphase system. For the cold state test model of large equipment using similarity theory, visual analysis techniques such as high-speed dynamic recording of flow field characteristics and PIV (particle image velocimetry), quantitative measurement techniques such as image analytical processing, mixing time determination, and chaos mathematical analysis can be used to realize quantitative characterization of the mixing degree of the nonlinear flow field. Furthermore, studies should look at the multi-field coupling mechanism of electric–magnetic–flow–heat–particles–components in gas–liquid–solid multiphase systems, including various transfer processes and metallurgical chemical reaction rules in actual metallurgical reactors. The results could be used to simulate and analyze the cooperative coupling laws of single and multiple associated reactors to optimize and improve the existing process and develop new carbon energy-conserving metallurgical processes and reactors.

(6) Rational design and fabrication of special alloys for cryogenic environments

Governments around the world are focusing on innovation and development of equipment in clean energy, aerospace, and other areas. Key components in the equipment often experience cryogenic environments, such as superconducting coils of magnetic confinement fusion reactors (~4 K), aerospace liquid oxygen/liquid hydrogen engines (~20 K), and wind tunnels with high Reynolds numbers (~77 K). This results in the need for exceptionally stringent requirements for the involved special alloys. Currently, special alloys in cryogenic environments face various challenges including inferior performance, ambiguous regulation mechanisms for their microstructures and properties, and immature preparation processes. These challenges largely limit improvements in aircraft manufacturing technology and the utilization of clean energy. There are many scientific problems that need to be solved in the rational design and preparation of special alloys for cryogenic environments. First, precise control of phase stability is required during cryogenic service. This mainly includes the mechanism of the austenite stacking fault energy in special alloys under cryogenic conditions, the effective control of phase stability, and the role of their interactions in different cryogenic properties, which in turn guides the alloy composition design and fabrication process. Second, systematic study is required for the multiphase microstructure evolution behavior and the strengthening and toughening mechanism during the integrated processing of melting–forging/rolling–heat treatment–welding for cryogenic special alloys. This includes the principle of forward/reverse phase transformation, alloy element partitioning, precipitation control, and cryogenic deformation. The microstructure–property relationships need to be determined among typical processing routes, multiphase microstructure components, and mechanical properties. Third, in complex cryogenic environments, it is necessary to study the failure modes and mechanisms under multi-field coupled service conditions with highly corrosive media over wide temperature ranges and under cyclic loading. This should include the mutual matching mechanism of multiple mechanical and physical properties at low temperatures, cryogenic failure behaviors under the coupling of thermal fatigue, wear, and corrosion, and the relationship between service performance and failure mechanisms. The results could be used to provide guidance for alloy design and fabrication process optimization of the cryogenic special alloys.

(7) Integrated monolithic electrodes for highly efficient electrochemical energy storage

Lithium-ion batteries occupy the majority of the market in the field of electrochemical energy storage. However, their present energy densities and power densities still need to be improved to meet growing social development. It is important to develop a new generation of lithium batteries with high specific energy, high power density, high stability, long life spans, high safety, and low cost. The key to achieving this goal is to have a clear understanding of the electrochemical energy storage mechanism of each involved active electrode material, and to carry out system design at the level of cell components and the overall electrode architecture. Therefore, research has focused on the design and fabrication of integrated monolithic electrodes with various compositions and structures. The developed electrodes will have excellent ion–electron mixed conductivities and could eliminate the use of inactive components such as binders. They will also have a suitable pore structure to maintain high structural stability during the charge–discharge process. To date, the research in this area has focused on the following aspects: advanced electrode structure design, simple electrode fabrication strategies, design and selection of current collectors and loading of active components, increasing the loading mass of active materials in area and volume, improving the conductivity of the overall electrode, matching of cathodes and anodes (construction of a full cell), development of flexible or thick electrodes, and determining the working or electrochemical reaction mechanism of the electrode. The structural design and simple fabrication of integrated monolithic electrodes with high active material loads are technical bottlenecks that need to be solved in this field.

(8) Research on high-strength high-toughness and low-density steel

Low-density steel, also known as lightweight alloy steel, is a lightweight material that reduces the density of the alloy by adding lightweight elements such as Al, Mn, and C. Research has shown that adding Al at a mass fraction of 1% can reduce the density of the steel by 1.3%. Low-density steel has broad application prospects in lightweight and safe service in vehicles, ships, aerospace and military fields. At the beginning of the 21st century, a study by the Max Planck Society in Germany showed that Fe–Mn–A1–C high-strength, high-toughness, and low-density steel had excellent potential for mass reduction, which was a driver for research on the use of low-density steel in automobiles. In 2015, POSCO in Republic of Korea trialed industrial production of rolling low-density steel, and in 2022, Xingcheng Special Steel in China trialed industrial production of high-strength, high-toughness, and low-density steel plates. Additionally, companies such as JFE and Nippon Steel in Japan, ThyssenKrupp in Germany, and Baowu and Ansteel in China have conducted research on and trialed production of low-density steel. However, further development and application of high-strength, high-toughness and low-density steel are restricted, due to factors such as manufacturing costs, surface quality and application technology. To date, research on high-strength, high-toughness, and low-density steel has focused on Fe–Mn–Al–C low-density steel. The main research directions include single ferrite steel, ferrite-based dual-phase steel, austenite-based dual-phase steel, and austenitic steel. There are still many scientific issues that need to be studied for the composition design, microstructure control, and service performance of Fe–Mn–Al–C low-density steel.

(9) Efficient preparation and catalytic mechanism of super-dispersed single-atom alloy catalysts

Single-atom alloy catalysts (SAACs) are usually prepared by dispersing a single atom of an active metal (typically a precious metal) in a second metal support (commonly a non-precious metal). SAACs have attracted attention in recent years because they have high utilization efficiency of noble metal atoms, high catalytic activity, and high selectivity. Since Sykes and colleagues proposed the concept of SAACs [Pd_1/Cu(111)] in 2012, scientists worldwide have explored various preparation methods of SAACs and gradually applied them to catalytic reactions such as fuel cells, electrolytic water, selective hydrogenation, and CO oxidation. To date, research on SAACs has focused on three aspects. First, exploring facile and efficient strategies to prepare SAACs with high atom pairing ratios and to precisely adjust the interactions between the active site and surrounding atoms. Second, revealing the structure–activity relationship between single-atom alloy structures and catalytic performance and the catalytic mechanism at the atomic level using *in situ* fine structure analysis and theoretical calculations. This could be used to provide a theoretical basis for the rational design of functional SAACs. Third, developing macro-preparation process for SAACs with adjustable noble metal loading, which will bridge the gap between fundamental research and industrial application. Because of their low noble metal loading and excellent catalytic activity, selectivity, and stability, super-dispersed SAACs will be key for the development of industrial catalysis.

(10) Selective confined mass transport membrane for ion separation

Ion-selective separation is an important area of membrane separation technology. This technique has been applied to lithium extraction from salt lakes, saltwater purification, high-salinity wastewater resource recovery, and flow batteries. The performance of traditional polymer membrane materials is restricted by the trade-off effect, where flux and selectivity cannot be improved simultaneously. Confined mass transfer membranes, which can be constructed using artificially engineered channels at the sub-nanometer scale, have unique mass transfer characteristics and are promising for use in this area. Currently, research on selective ion-transport membranes is divided into two areas. The first involves the fundamental exploration of separation mechanisms to explore the factors influencing mass transfer dynamics and selectivity at the microscale, such as the channel geometric structure and interfacial physicochemical properties. The results from this could aid in membrane design. The second involves the design of membrane materials to achieve ultrafast mass transfer using materials with different sizes, functional groups, and interfacial charges, such as COFs and MOFs. Future research will look at *in situ* visualization of confined channels to establish an effective connection between ideal mass transfer models and the actual performance of separation membranes. This will be achieved through the manufacture of confined transport membranes with high mass transfer rates and selectivity, the transition from laboratory-scale specifications to large-scale production, and realization of industrial development.

(11) Intrinsically safe battery systems for renewable energy storage

Large-scale energy storage stations have strict requirements for battery safety. An intrinsically safe battery is one with an inner safety mechanism, which can improve the safety performance in the internal structure, and materials that can effectively prevent and control dangerous situations such as thermal runaway, explosion, and leakage. Current research in the field of intrinsically safe batteries is creating new breakthroughs. Scientists are committed to developing new materials and optimizing the battery structure to improve the intrinsic safety performance and electrochemical performance of batteries, for example, by the addition of flame retardants to effectively inhibit the combustion of electrolytes, development of intrinsic flame-retardant polymer electrolytes to improve the safety of solid-state batteries, and suppression of lithium dendrite to improve the safety of lithium metal anodes. Research on intrinsically safe batteries has focused on the following aspects: improving the electrochemical stability to prevent side reactions, electrolyte decomposition, or instability of electrode materials during charging and discharging; improving the thermal safety of batteries in high-temperature environments by developing non-flammable (or flame-retarding) battery materials and upgrading the battery thermal management system to prevent overheating from causing battery runaway, combustion, or explosion; improving the mechanical stability of the battery by addressing external impact and internal stress of the battery to avoid safety hazards such as battery rupture or an internal short circuit; and replacing the traditional organic electrolytes with solid electrolytes or aqueous electrolytes to improve the safety and stability of the battery and solve the problems of combustion and leakage of organic electrolytes.

1.2 Interpretations for three key engineering research fronts

1.2.1 Renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials

Many countries and regions have development strategies for green biorefineries. The 14th Five-Year Plan in China highlights that deep integration of the energy and manufacturing industries with biotechnology will be required to establish a green, low-carbon, and non-toxic circular economy. The Bold Goals for U.S. Biotechnology and Biomanufacturing plan is to achieve gigaton-level CO_2 fixation through bioconversion within the next 9 years at a cost of less than $100 per metric ton. The use of renewable energy to drive the process of bioconversion of CO_2 to chemicals, fuels, and materials reduces carbon emissions, which is a focus for biorefineries. This will lower human dependence on fossil energy to trigger a change in industrial patterns and facilitate the transition to a green economy. Since third-generation biorefineries were proposed in 2020, research on biological carbon sequestration coupled with photocatalysis and electrocatalysis has developed rapidly to achieve carbon peak and carbon neutrality goals. Various pathways and mechanisms have been developed. Biocatalysts can directly take up electrons provided by photo- and electrocatalysts for CO_2 sequestration, and use formic acid, acetic acid, methanol, and other primary products of CO_2 reduction for fermentation. Enzyme engineering and synthetic biology has rapidly progressed and expanded the product spectrum of biological carbon sequestration driven by renewable energy. A series of products, including raw material chemicals such as L-lactic acid, dihydroxyacetone, glycolic acid, and biodegradable plastics such as PLA and PHA, can be produced with CO_2 as the only carbon source. However, compared with traditional methods conducted under high temperature and pressure, there is an efficiency bottleneck for the use of renewable energy to drive biological carbon sequestration. The main solutions to this are development of highly active enzymes and strains and rational design of efficient biological pathways for carbon sequestration; improvement of the utilization of renewable energy and development of photo- and electrocatalysts with bioaffinity and low toxicity; and optimization of the thermodynamic and kinetic adaptation of artificial modules and biocatalytic modules, or decoupling of these modules to ensure optimum efficiency.

The main countries with the greatest output of core papers in recent years on “bioconversion of carbon dioxide to chemicals, fuels, and materials driven by renewable energy” are shown in Table 1.2.1, and the main institutions are shown in Table 1.2.2. The main contributor to these core papers is China (41.3% of the total), followed by the USA, India, Republic of Korea, and Germany (all > 10% of the total). The main institutions in China are Chinese Academy of Sciences and Tianjin University. Figures 1.2.1 and 1.2.2 show the collaboration network among major countries and among major institutions. Scientists have established extensive global collaborations in this field. China’s largest collaborator is the USA. Among the cited core papers, China accounted for 52.02% of the total (Table 1.2.3 and 1.2.4). Among the top ten major producing institutions of the citing papers, all, except for King Abdulaziz University, were Chinese universities or institutes. These institutions included Chinese Academy of Sciences, Jiangsu University, and Tsinghua University.

Renewable energy-driven bioconversion of CO_2 to chemicals, fuels, and materials has developed rapidly in recent years. A roadmap for the engineering research front of “renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials” is shown in Figure 1.2.3. The key problem with coupling artificial devices that transform renewable energy with biocatalysts is the coupling mechanism. In future studies, it is important to develop techniques to identify the interaction mechanism between artificial devices and biological components. This will promote the development of new and efficient systems and new models. Biocatalysts are central to this process. Progress in the development of robust and efficient industrial enzymes and industrial strains will determine the industrialization process for biological carbon sequestration driven by renewable energy. This will speed

Table 1.2.1 Countries with the greatest output of core papers on “renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	38	41.30	5 087	133.87	2019.0
2	USA	24	26.09	3 911	162.96	2018.7
3	India	16	17.39	2 676	167.25	2019.3
4	Republic of Korea	10	10.87	1 708	170.80	2018.4
5	Germany	10	10.87	1 114	111.40	2019.2
6	Australia	9	9.78	1 480	164.44	2019.0
7	UK	8	8.70	922	115.25	2019.0
8	Saudi Arabia	5	5.43	871	174.20	2019.0
9	Israel	4	4.35	635	158.75	2019.0
10	Canada	4	4.35	538	134.50	2018.0

Table 1.2.2 Institutions with the greatest output of core papers on “renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Shoolini University	5	5.43	707	141.40	2020.0
2	Chinese Academy of Sciences	5	5.43	536	107.20	2019.4
3	Harvard University	4	4.35	780	195.00	2018.5
4	University of California, Berkeley	4	4.35	635	158.75	2019.0
5	University of Cambridge	4	4.35	520	130.00	2018.8
6	Lawrence Berkeley National Laboratory	3	3.26	538	179.33	2018.7
7	Korea Advanced Institute of Science and Technology	3	3.26	459	153.00	2018.0
8	Konkuk University	3	3.26	361	120.33	2018.3
9	Tianjin University	3	3.26	360	120.00	2018.7
10	Virginia Polytechnic Institute and State University	3	3.26	290	96.67	2019.0

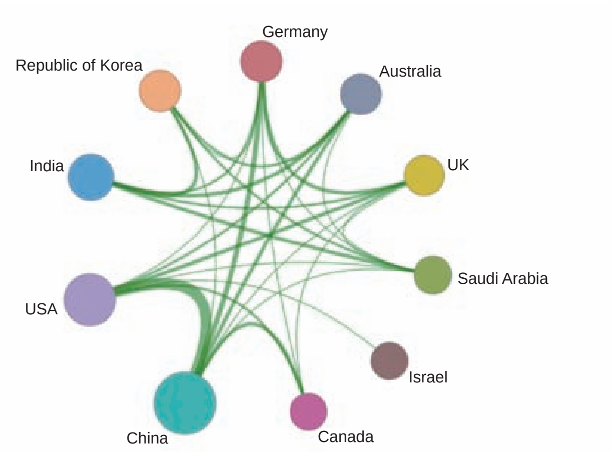

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials”

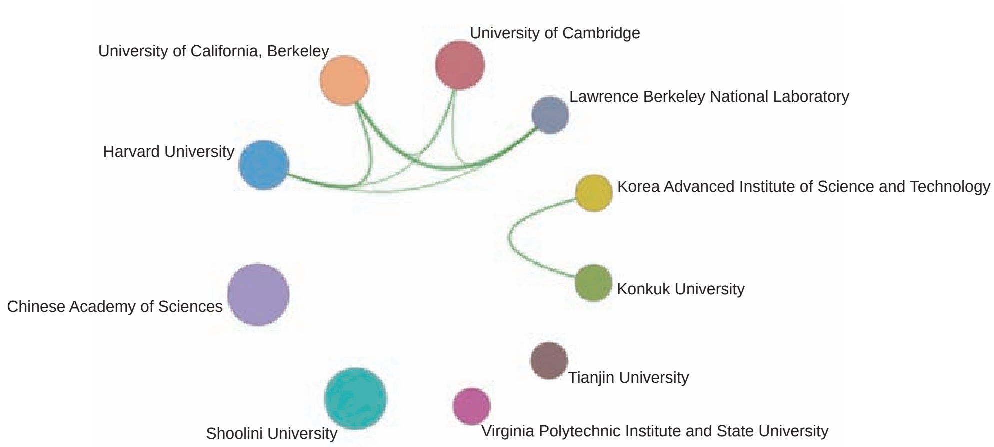

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials”

Table 1.2.3 Countries with the greatest output of citing papers on “renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	6 308	52.02	2021.0
2	USA	1 196	9.86	2020.7
3	India	1 130	9.32	2021.1
4	Republic of Korea	695	5.73	2020.8
5	Australia	481	3.97	2020.8
6	Germany	476	3.93	2020.8
7	Saudi Arabia	423	3.49	2021.1
8	UK	408	3.36	2020.9
9	Iran	355	2.93	2020.8
10	Spain	333	2.75	2020.8

Table 1.2.4 Institutions with the greatest output of citing papers on “renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	793	33.47	2021.0
2	Jiangsu University	202	8.53	2020.9
3	Tsinghua University	193	8.15	2021.1
4	University of Science and Technology of China	185	7.81	2021.3
5	Tianjin University	178	7.51	2021.0
6	Zhengzhou University	174	7.34	2021.2
7	Hunan University	157	6.63	2021.0
8	King Abdulaziz University	132	5.57	2021.0
9	Fuzhou University	121	5.11	2020.8
10	Harbin Institute of Technology	120	5.07	2021.1

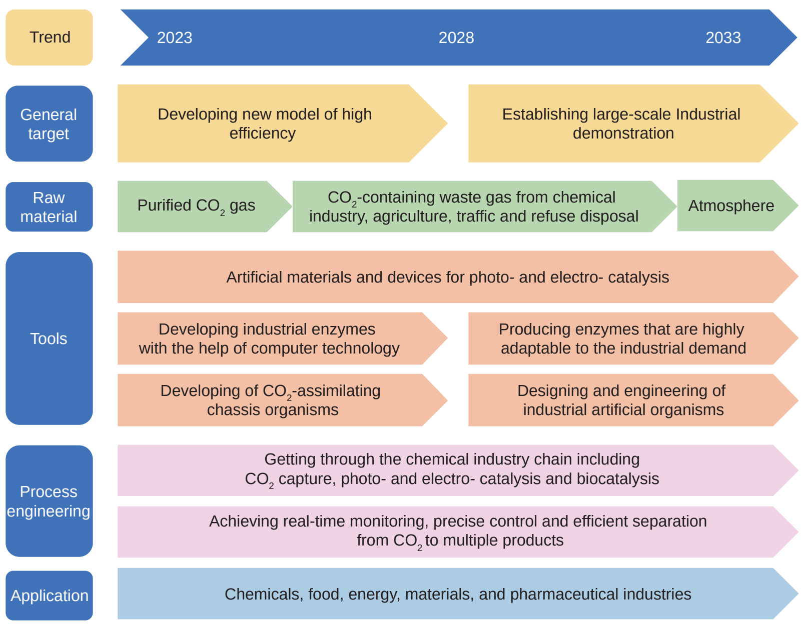

Figure 1.2.3 Roadmap of the engineering research front of “renewable energy-driven bioconversion of carbon dioxide to chemicals, fuels, and materials”

up considerably with application of computer technology, such as big data and artificial intelligence, and advanced physical and chemical technology to the screening, modification, and design of industrial enzymes and industrial strains. Technical autonomy of core enzymes and core strains will be achieved in the next few years. Research on advanced industrial reactors should be intensified to achieve real-time monitoring, precise regulation, and efficient separation of CO_2 from various fuels and chemicals according to production needs. This will result in establishment of targeted and efficient production routes.

1.2.2 Chaotic nonlinear enhancement technology of metallurgical flow field

Metallurgical reactors, which are used as reaction vessels in the metallurgical industry, play a pivotal role in industrial processes. These reactors provide a space for intricate multiphase mixing and reaction systems, encompassing the flow, mixing, reaction, heat transfer, and mass transfer of gas, solid, and liquid phases. They serve as a convergence point for micro-scale reactions and macroscopic processes. The metallurgical flow field, functioning as a conduit for energy and mass transfer, has a decisive influence over the synergy of these three domains and the overall system performance. Over the years, significant advancements in measurement and data acquisition techniques for metallurgical reaction systems have greatly enhanced the analytical capabilities of metallurgical flow fields under specific conditions. This progress has contributed to a deeper understanding of the intricate chemical processes involved. However, the design, optimization, and operation of these fields are still heavily reliant on empirical data. The chaotic nonlinear enhancement technology of metallurgical flow represents a cutting-edge research direction in the field of metallurgical science and engineering. This technology integrates knowledge from fluid dynamics, chaos theory, and nonlinear science. Its primary aim is to optimize the behavior of metallurgical flow fields to enhance production efficiency.

Metallurgical multiphase flow is a typical nonlinear process that deviates from equilibrium. It encompasses numerous complex nonlinear dynamic mechanisms and exhibits spatiotemporal cross-scale coupling characteristics. This leads to a lack of synergy between mixing, heat/mass transfer, and chemical reaction processes in metallurgical reaction systems, which poses challenges for effective control, enhancement, and engineering upscaling. The core direction of this field focuses on the synergistic evolution of continuous and dispersed phase topological structures in multiphase systems within metallurgical reactors, the interaction of chaotic flow mixing characteristics with multi-physics fields, and their correlation with transfer performance. The research pathway for chaotic nonlinear enhancement of metallurgical flow is as follows. First, chaos theory is used to describe the multiphase nonlinear systems in metallurgical processes, and rapid inter-phase heat and mass transfer is achieved via chaotic enhancement to accelerate chemical reaction rates. Second, the synergistic coupling of multi-physics fields, including flow, temperature, and composition fields, is realized, which enables effective control of the flow distribution. Third, through the enhancement of the synergy and uniformity of flow-transfer-reaction processes, efficient and uniform mixing is achieved along with intensified heat and mass transfer. This forms the theoretical foundation for the enhancement of metallurgical processes and optimization of reactors.

The major contributors to the engineering research front on “chaotic nonlinear enhancement technology of metallurgical flow field” in recent years are detailed in Table 1.2.5 for countries and Table 1.2.6 for institutions. Among the countries, China holds the lead position, followed by Iran. Among the institutions, the Islamic Azad University ranks first, while China’s Xi’an Jiaotong University, Shanghai Jiao Tong University, and the Chinese Academy of Sciences also rank highly. The collaborative network among the main countries and institutions is illustrated in Figures 1.2.4 and 1.2.5. China occupies a central position in this collaborative network, forming partnerships with multiple countries, and notably has a prominent collaboration with Pakistan. Pakistan is an important node in the network as well, and cooperates with all countries except for the UK and Singapore. Collaborations between institutions are tightly interconnected within Asia, with the Islamic Azad University holding a central position in the collaborative network and partnering with multiple institutions. As indicated in Table 1.2.7, China has the highest number of core paper citations, with 2 490 citations accounting for 26.51% of the total. China is the leader for both the core paper count and cited core paper count, which highlights the advanced position of Chinese scholars in this field. This indicates that Chinese scholars are at the forefront of research in this domain and are keeping abreast of the dynamics in this cutting-edge field.

Chaotic nonlinear enhancement of metallurgical flow involves using chaotic nonlinear theory to study the mixing mechanism of multiphase flow in metallurgical processes and analyzing the formation, transport, and transformation of multi-scale flow structures. To date, because of limitations in experimental measurement techniques and the development of multi-scale simulation methods, research on chaotic flow in extreme and unconventional metallurgy and the scaling up of large-scale equipment remains limited. Moreover, this research direction involves the intersection of multiple disciplines, including metallurgy, fluid dynamics, and physics. There are three future research directions (Figure 1.2.6). First, research on chaotic flow enhancement in extreme and unconventional metallurgical reaction fields by advancing chaotic flow enhancement under extreme and unconventional metallurgical process conditions, involving electric, magnetic, and thermal stress fields. This will break down interdisciplinary barriers and enhance the systematic and universal aspects of nonlinear chaotic theory. Second, research on mechanisms and criteria for amplifying chaotic flow in super-large metallurgical smelting equipment by overcoming the mechanisms and criteria for chaotic flow amplification in metallurgical flow fields and addressing issues arising from the lack of theoretical guidance in the amplification of super-large smelting equipment, including distortion, operational instability, and process mismatch. Third, research on metallurgical flow field chaos nonlinear enhancement technology using machine learning by constructing metallurgical flow field nonlinear enhancement models using machine learning to overcome the complex coupling mechanisms of various factors in metallurgical processes. This will strengthen the intelligent development of metallurgical systems through software and hardware using machine learning.

Table 1.2.5 Countries with the greatest output of core papers on "chaotic nonlinear enhancement technology of metallurgical flow field"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	40	33.33	3 192	79.80	2019.0
2	Iran	26	21.67	2 411	92.73	2018.5
3	USA	20	16.67	1 632	81.60	2018.4
4	India	20	16.67	1 529	76.45	2019.8
5	Pakistan	16	13.33	992	62.00	2019.9
6	Saudi Arabia	13	10.83	1 099	84.54	2019.6
7	UK	8	6.67	872	109.00	2019.2
8	Vietnam	8	6.67	540	67.50	2019.9
9	Singapore	7	5.83	454	64.86	2018.7
10	The United Arab Emirates	6	5.00	393	65.50	2019.3

Table 1.2.6 Institutions with the greatest output of core papers on "chaotic nonlinear enhancement technology of metallurgical flow field"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Islamic Azad University	10	8.33	893	89.30	2018.8
2	Xi'an Jiaotong University	8	6.67	499	62.38	2018.5
3	Ton Duc Thang University	7	5.83	491	70.14	2019.7
4	Nanyang Technological University	6	5.00	410	68.33	2019.0
5	Shanghai Jiao Tong University	4	3.33	453	113.25	2019.8
6	Chinese Academy of Sciences	4	3.33	433	108.25	2017.8
7	King Fahd University of Petroleum and Minerals	4	3.33	410	102.50	2020.2
8	Iran University of Science and Technology	4	3.33	309	77.25	2019.0
9	Indian Institute of Technology	4	3.33	284	71.00	2019.0
10	COMSATS University Islamabad	4	3.33	229	57.25	2020.2

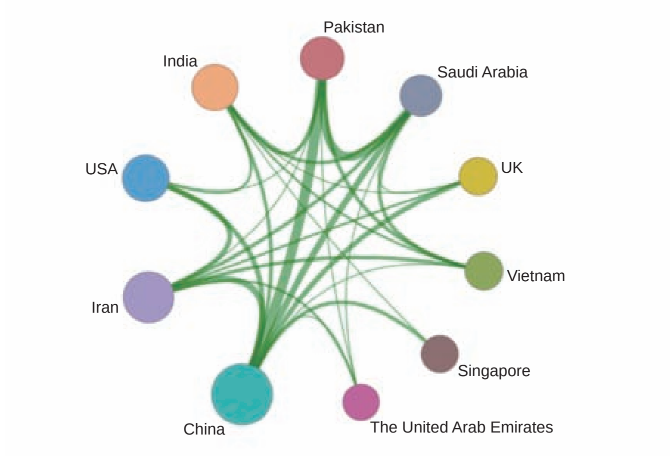

Figure 1.2.4 Collaboration network among major countries in the engineering research front of “chaotic nonlinear enhancement technology of metallurgical flow field”

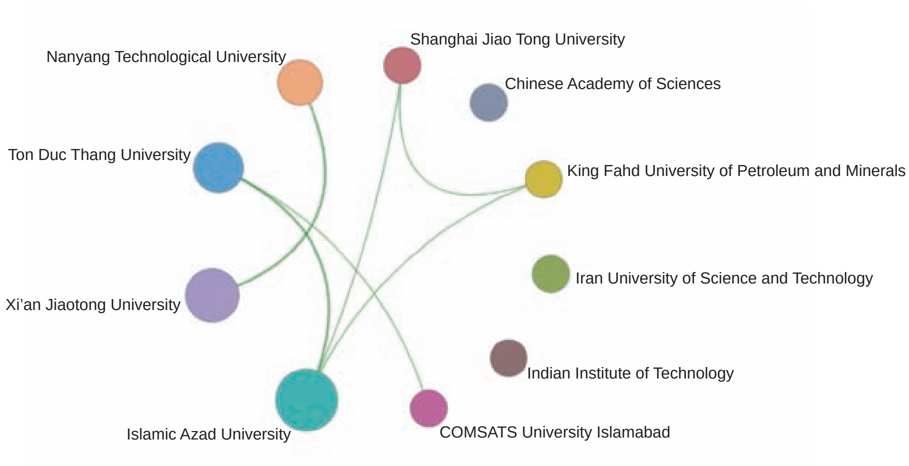

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “chaotic nonlinear enhancement technology of metallurgical flow field”

Table 1.2.7 Countries with the greatest output of citing papers on “chaotic nonlinear enhancement technology of metallurgical flow field”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 490	26.51	2021.0
2	Saudi Arabia	1 327	14.13	2021.3
3	Pakistan	1 157	12.32	2021.1
4	India	1 050	11.18	2021.2
5	Iran	1 003	10.68	2020.5
6	USA	560	5.96	2020.8
7	Egypt	458	4.88	2021.5
8	UK	366	3.90	2021.1
9	Vietnam	351	3.74	2020.2
10	Malaysia	315	3.35	2021.0

Table 1.2.8 Institutions with the greatest output of citing papers on "chaotic nonlinear enhancement technology of metallurgical flow field"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	King Khalid University	360	14.84	2021.5
2	Islamic Azad University	306	12.61	2020.5
3	King Abdulaziz University	301	12.41	2021.2
4	Ton Duc Thang University	279	11.50	2020.0
5	Prince Sattam Bin Abdulaziz University	230	9.48	2021.6
6	Xi'an Jiaotong University	195	8.04	2020.9
7	China Medical University	191	7.87	2021.5
8	COMSATS University Islamabad	169	6.97	2021.4
9	Babol Noshirvani University of Technology	159	6.55	2019.4
10	Duy Tan University	129	5.32	2020.5

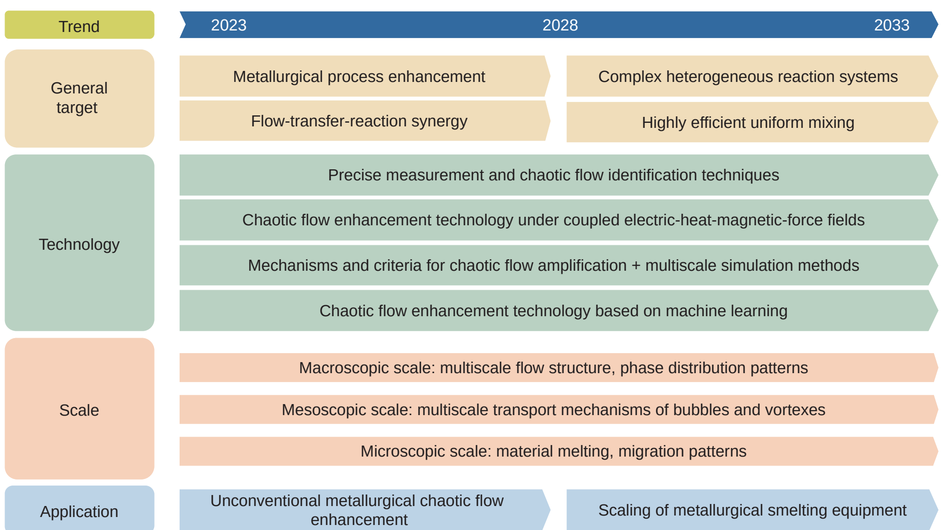

Figure 1.2.6 Roadmap of the engineering research front of "chaotic nonlinear enhancement technology of metallurgical flow field"

1.2.3 High-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization

The use of renewable energy to drive electrochemical reduction of CO_2 to produce high value-added chemicals provides an effective way to solve the energy crisis and environmental problems. In recent years, research on the development of electrocatalyst materials for CO_2 reduction has made great progress in terms of selectivity, efficiency, and reaction rate, and is moving towards practical applications. Electrochemical reduction of CO_2 can be used to produce various chemicals, such as alcohols, oxygenates, syngas, and olefins, on a large scale. The shift to renewable energy could greatly reduce CO_2 emissions.

Because of its high thermodynamic stability, CO_2 is difficult to activate. Additionally, it is difficult to generate high value-added C_{2+} products through C–C coupling. Recently, significant progress has been made in the design of highly active or highly selective electrocatalysts and the mechanism of CO_2RR. There are three main areas of focus in current research.

First, design and controllable preparation of highly efficient electrocatalysts through control of the crystal surface, morphology, and surface electronic structure to improve the CO_2RR activity, selectivity, and stability. Second, various *in situ* characterization methods, such as *in situ* infrared spectroscopy, *in situ* Raman spectroscopy, and *in situ* electron microscopy, are used to monitor the evolution of the reaction intermediates and catalyst surface structures during the CO_2RR process. The results are used to reveal the regulatory effects of the catalyst surface and electronic structure on the catalytic reaction and its kinetic mechanism. Third, design of the electrode structure through the modification of hydrophobic materials (such as polytetrafluoroethylene) and improvement of the hydrophobic performance of the electrode surface to avoid issues with flooding during long-term operation and improve the electrode stability. The structure of electrolytic reactor is optimized to enhance mass transfer and energy efficiency.

The major countries and institutions in recent years for output of core papers on the engineering research front of "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization" are shown in Tables 1.2.9 and 1.2.10, respectively. Among the major countries producing core papers, China is ranked first, with 71 core papers (66.36% of the total), which is much higher than the numbers produced in the USA, Australia, Canada, and other countries. Among the major institutions producing core papers, Chinese Academy of Sciences is ranked first, followed by University of Science and Technology of China, and Stanford University. The major collaborations among countries and institutions are plotted in Figures 1.2.7 and 1.2.8, respectively. Most of China's collaborations are with the USA, and it also closely cooperates with Australia, Canada, and Singapore. The top three countries in terms of the number of citing core papers are China, the USA, and Australia (Table 1.2.11). The proportion of citing papers from China is 57.95%, which indicates that Chinese scientists have paid close attention to the research trends in this area. Most of the major institutions producing citing core papers are in China, including Chinese Academy of Sciences, University of Science and Technology of China, and Tianjin University (Table 1.2.12)

It is an important to develop green and low-carbon energy technology to activate and transform CO_2 through electrocatalytic mild conditions to synthesize the chemicals needed for social and economic development. The electrocatalytic conversion of CO_2 is a complex multi-scale process, involving CO_2 molecular adsorption and conversion, nano-scale catalysts, micron-scale membrane electrodes, and macro-scale electrolyzers. Current research is mainly focused on finding and improving high-performance electrocatalysts. Future research should look at combining various *in situ* characterization methods for electrode morphology

Table 1.2.9 Countries with the greatest output of core papers on "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	71	66.36	17 849	251.39	2019.0
2	USA	31	28.97	8 069	260.29	2018.8
3	Australia	12	11.21	2 946	245.50	2018.9
4	Canada	11	10.28	4 406	400.55	2019.1
5	Republic of Korea	9	8.41	1 429	158.78	2018.8
6	Singapore	7	6.54	2 569	367.00	2018.9
7	Switzerland	4	3.74	764	191.00	2018.5
8	Germany	4	3.74	686	171.50	2018.8
9	France	4	3.74	681	170.25	2019.2
10	Denmark	3	2.80	749	249.67	2018.3

Table 1.2.10 Institutions with the greatest output of core papers on "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	25	23.36	6 474	258.96	2019.1
2	University of Science and Technology of China	9	8.41	2 517	279.67	2019.4
3	Stanford University	7	6.54	1 813	259.00	2019.3
4	Tianjin University of Technology	6	5.61	1 616	269.33	2018.7
5	Beijing University of Chemical Technology	6	5.61	1 260	210.00	2019.0
6	Nanyang Technological University	5	4.67	1 846	369.20	2019.0
7	SLAC National Accelerator Laboratory	5	4.67	1 032	206.40	2019.4
8	University of Toronto	4	3.74	2 155	538.75	2020.0
9	Tianjin University	4	3.74	2 082	520.50	2018.0
10	Yale University	4	3.74	1 860	465.00	2017.5

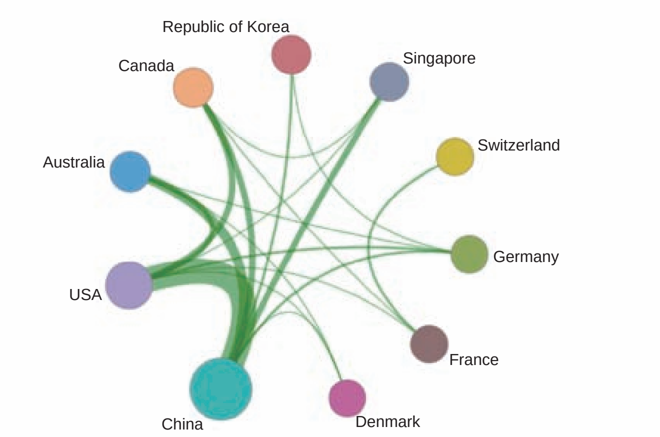

Figure 1.2.7 Collaboration network among major countries for the engineering research front of "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization"

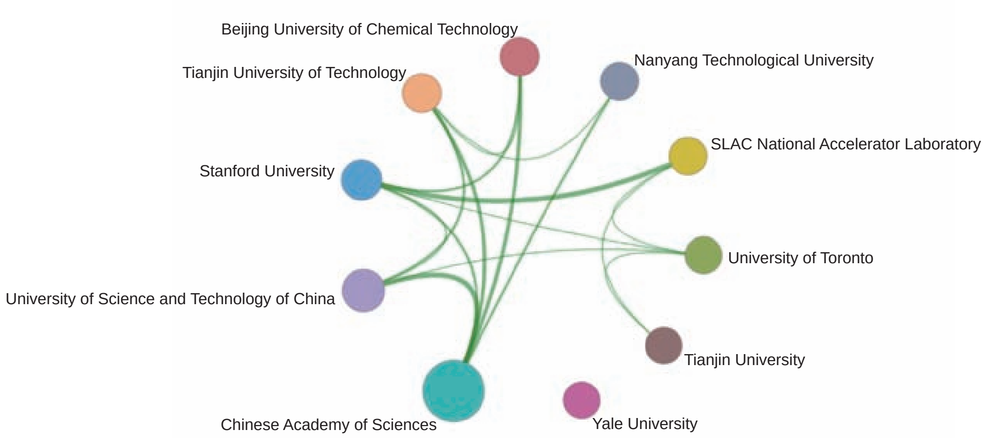

Figure 1.2.8 Collaboration network among major institutions for the engineering research front of "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization"

evolution, reaction process condition optimization, electrode/electrolyte interface evolution, mass transfer transportation optimization, catalyst stability improvement, and electrolyte/solvent effect. Additionally, for the future industrial application of electrocatalytic reduction of CO_2, the following points need to be considered: determining the practical application objectives, evaluating the economics of chemical products and market supply and demand, expanding the scale of CO_2 electrolyzers, improving the long-term continuous operation stability of electrocatalysts, and calculating the cost of product separation and raw material recovery. The roadmap of the engineering research front of "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization" is shown in Figure 1.2.9.

Table 1.2.11 Countries with the greatest output of citing papers on "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization"

No.	Country/Region	Citing papers	Percentage of citing papers/%	Mean year
1	China	8 508	57.95	2021.0
2	USA	1 928	13.13	2020.6
3	Australia	746	5.08	2020.8
4	Republic of Korea	612	4.17	2020.9
5	Germany	524	3.57	2020.8
6	Canada	521	3.55	2020.7
7	India	424	2.89	2021.1
8	UK	407	2.77	2020.8
9	Singapore	405	2.76	2020.8
10	Japan	386	2.63	2020.8

Table 1.2.12 Institutions with the greatest output of citing papers on "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	1 705	36.28	2020.9
2	University of Science and Technology of China	525	11.17	2021.0
3	Tianjin University	405	8.62	2021.0
4	Tsinghua University	374	7.96	2021.0
5	Beijing University of Chemical Technology	303	6.45	2020.8
6	Zhengzhou University	300	6.38	2021.2
7	Soochow University	260	5.53	2020.9
8	Nanyang Technological University	230	4.89	2020.7
9	Zhejiang University	209	4.45	2021.0
10	Shenzhen University	196	4.17	2021.1

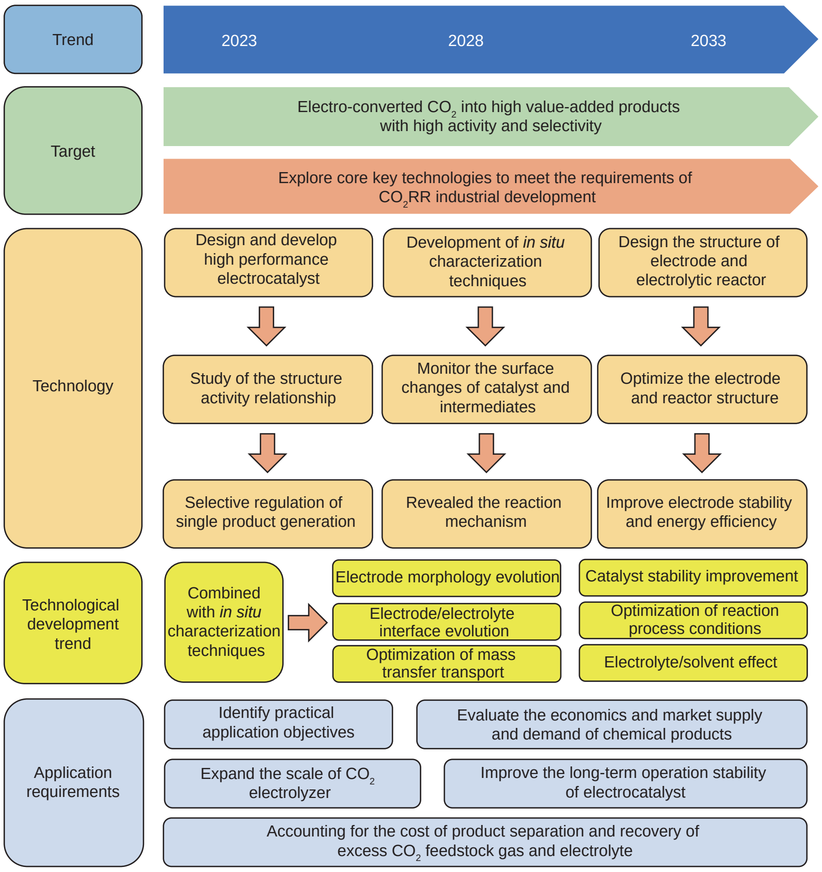

Figure 1.2.9 Roadmap of the engineering research front of "high-performance electrocatalysts and electrolysis systems for CO_2 conversion and utilization"

2 Engineering development fronts

2.1 Trends in Top 11 engineering development fronts

The Top 11 engineering development fronts as assessed by the Field Group of Chemical, Metallurgical, and Materials Engineering are shown in Table 2.1.1. "Design and preparation of metal matrix composites for high-temperature environments", "construction and large-scale manufacturing technology of high-efficiency photovoltaic devices", "low-temperature and low-pressure thermal catalytic ammonia synthesis over a wide loading range", and "development of ironmaking technology for hydrogen-rich carbon cycle blast furnaces" were recommended by experts directly. The other fronts were chosen by a panel of experts according to core-paper statistics provided by Clarivate. The annual numbers of core patents for all fronts show overall growth, especially for "integration of large language models for the design and synthesis of advanced chemical engineering materials", "efficient and energy-saving separation technologies for energy intensive chemical processes", and "development of ironmaking technology for hydrogen-rich carbon cycle blast furnaces" (Table 2.1.2).

(1) Metallurgical low-carbon utilization of renewable energy

The smelting process of complex metal materials requires a large amount of electricity and relies on the reduction characteristics of fossil fuels and combustion heating. This is the key to restrict the low-carbon sustainable development of the metallurgical

Table 2.1.1 Top 11 engineering development fronts in chemical, metallurgical, and materials engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Metallurgical low-carbon utilization of renewable energy	520	223	0.43	2020.4
2	Integration of large language models for the design and synthesis of advanced chemical engineering materials	482	1 354	2.81	2020.9
3	Design and preparation of metal matrix composites for high-temperature environments	596	1 033	1.73	2019.7
4	Efficient and energy-saving separation technologies for energy intensive chemical processes	697	774	1.11	2020.0
5	Chaotic enhancement technology for heating process in metallurgical furnaces	775	501	0.65	2019.8
6	Construction and large-scale manufacturing technology of high-efficiency photovoltaic devices	705	1 066	1.51	2019.4
7	Low-temperature and low-pressure thermal catalytic ammonia synthesis over a wide loading range	540	890	1.65	2019.5
8	Development of ironmaking technology for hydrogen-rich carbon cycle blast furnaces	353	582	1.65	2020.2
9	Development and application of ultra-high energy density aluminum-air batteries	400	656	1.64	2019.7
10	Key preparation technologies and applications of high-purity metals, alloys, and materials	358	335	0.94	2019.8
11	Molecular design and large-scale preparation of new bio-aviation fuels	208	464	2.23	2019.6

Table 2.1.2 Annual number of core patents published for the Top 11 engineering development fronts in chemical, metallurgical, and materials engineering

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Metallurgical low-carbon utilization of renewable energy	40	48	48	90	140	154
2	Integration of large language models for the design and synthesis of advanced chemical engineering materials	12	22	46	66	123	213
3	Design and preparation of metal matrix composites for high-temperature environments	84	101	87	93	106	125
4	Efficient and energy-saving separation technologies for energy intensive chemical processes	83	90	92	105	131	196
5	Chaotic enhancement technology for heating process in metallurgical furnaces	97	113	109	132	157	167
6	Construction and large-scale manufacturing technology of high-efficiency photovoltaic devices	126	142	108	95	100	134
7	Low-temperature and low-pressure thermal catalytic ammonia synthesis over a wide loading range	101	76	93	81	86	103
8	Development of ironmaking technology for hydrogen-rich carbon cycle blast furnaces	32	48	39	55	59	120
9	Development and application of ultra-high energy density aluminum-air batteries	52	53	77	77	68	73
10	Key preparation technologies and applications of high-purity metals, alloys, and materials	46	50	55	53	72	82
11	Molecular design and large-scale preparation of new bio-aviation fuels	32	37	32	28	36	43

industry. Renewable energy can provide clean electricity, biomass energy, and green hydrogen with reducibility and combustion heating properties. It is expected that low-carbon green transformation of the industry will be achieved with the efficient application of renewable energy in metallurgy. China has developed a relatively complete iron and steel hydrogen metallurgy system and conducted metallurgy demonstration projects for more than one million tons of hydrogen. Hydropower silicon and hydropower aluminum have been achieved in Yunnan, China with an output value of more than 100 billion RMB. However, in the field of renewable energy combustion and reduction technology, there are still many problems to be further studied. The future development direction is mainly concentrated in three areas. First, metallurgical energy systems should be combined with multi-energy complementation and energy storage to develop clean energy supply systems using wind, light, water, hydrogen, and metallurgical waste heat and energy. Second, new technology for deep reduction of metallurgical slag by swirl injection of biomass fuel oil should be developed to replace fossil energy reducing agents with renewable energy. Third, swirl atomization enhanced combustion technology of biomass fuel should be developed to improve combustion and heating efficiency of macromolecular, low calorific value biomass fuel, and replace fossil fuel with renewable energy. These changes will provide clean energy, improve the efficiency of energy consumption, and reduce carbon emissions over the full lifecycle.

(2) Integration of large language models for the design and synthesis of advanced chemical engineering materials

The development cycle for new chemical materials spans 15–25 years, requires significant investment, and is heavily reliant on expert experience. As the field has matured, the size of the total dataset has increased but data for some specific sub-systems are limited. Access to experts with experience to discern patterns in new materials is becoming increasingly challenging, and there is an urgent need for a paradigm shift in research methodologies. At the beginning of 2023, ChatGPT emerged, closely followed by Llama, Claude, Wenxin Yiyan, and Wu Dao, marking the dawn of the era of large language models (hereafter referred to as large models). Characterized by their large scale, emergent properties, and universality, these models are promising for application in the chemical engineering sector and show potential for accelerating the design and fabrication of new materials. Large models can comprehensively hasten the development of new materials across various stages, including literature information extraction, material structure generation, material property prediction, synthesis condition optimization, and intelligent characterization. Literature information extraction serves as the primary means to integrate chemical material data. Large language models can refine the output of natural language models to make them structured information, and improve the quality of data. Material structure generation is a key technology for the reverse design of new materials, and could benefit from the emergent properties of large models in breaking human cognitive biases. Material property prediction is a prerequisite for high-throughput screening and could be enhanced by large models, which consolidate various smaller models within the field to enable precise prediction of various material properties. Synthesis condition optimization and intelligent characterization are core steps in exploring material fabrication techniques. Large models possess superior pattern-recognition capabilities, allowing for faster identification of optimal points.

(3) Design and preparation of metal matrix composites for high-temperature applications

Metal matrix composites (MMCs) are multiphase materials composed of a metal or alloy matrix and one or more types of reinforcement. These composites possess the combined characteristics of the metal or alloy matrix and the reinforcement, including high specific strength, specific modulus, low density, and good electrical and thermal conductivity. Consequently, they are used in many applications in the aerospace, automotive, electronic information, and national defense industries. However, most research on MMCs has focused on enhancing their mechanical properties at room temperature, particularly their strength and toughness, while high-temperature properties have received relatively little attention. Under high-temperature and stress conditions, solute atoms exhibit faster diffusion rates and are more vulnerable to adverse effects such as oxidation and corrosion from the service environment. Additionally, MMCs subjected to long-term use frequently experience failure in the form of thermal fatigue or creep damage. Consequently, their service lives tend to be shorter than those used at room temperature. This underscores the urgency for design of MMCs to meet the requirements of high-temperature use. Currently, material development efforts at both domestic and international levels are primarily focused on four aspects. First, high-throughput preparation and characterization of composites using material genetic engineering. Second, fine control of the configuration and interface in the material forming process. Third, short process manufacturing technology for producing large-size components of heat-resistant aluminum matrix composites. Forth, understanding the evolution, property degradation mechanisms, and control technology of composites used in high-temperature environments.

(4) Efficient and energy-saving separation technologies for energy intensive chemical processes

The chemical industry had large energy consumption and carbon emissions. Chemical separation processes account for approximately 70% of the total energy consumption in chemical product processing. Currently, although some industries have made significant improvements in technology and equipment, the overall technical level is still relatively low. The proportion of technology and equipment at an advanced international level in the entire industry is very small, and the energy utilization rate is approximately 15% lower than the average of developed countries. Some chemical products have an energy consumption more than 20% higher than those in developed countries. Improvements in production efficiency, energy conservation, emission reductions, and industrial upgrades can only be achieved by increasing technological innovation; vigorously developing and promoting new energy-saving processes, technologies, and equipment for chemical separation processes; reducing fossil energy consumption and improving energy utilization efficiency; and fully utilizing high-tech to enhance and transform traditional chemical industries. The future development of separation technology for energy intensive chemical processes should mainly focus on two aspects. First, development of alternative and efficient separation methods, such as molecular recognition separation technology, separation process integration, and intensification technology. Appropriate separation methods should be selected according to the characteristics of different separation systems to improve the energy utilization efficiency of the separation process. Second, development of new forms of renewable energy, such as solar energy, biomass energy, green hydrogen, and green electricity, to reduce the proportion of fossil energy used in the separation process. Development of new separation technologies using renewable energy could be used to promote the transition to a green, sustainable, and efficient chemical industry.

(5) Chaotic enhancement technology for heating process in metallurgical furnaces

The main method to achieve energy savings and efficiency improvements in metallurgical furnace is to strengthen the heating process. Traditional intensified heating mainly relies on increasing the amount of heating, which leads to high energy consumption and carbon emissions, and shortens the equipment lifecycle. Additional, the product quality does not meet the requirements for high-end uses. Chaotic enhanced heating technology in metallurgical furnace uses chaotic mathematical theory to establish a series of mathematical models of chaotic flow intensification, and then regulates the chaotic flow pattern to strengthen heat and mass transfer. Currently, industrial applications have been realized in molten pool melting furnaces and heating furnaces. Two key scientific problems, the enhancement mechanism of heat and mass transfer in furnaces and the multi-field collaborative enhancement mechanism, have not been solved. Consistency between the mathematical model and practical application is not sufficient. There are three main future directions. First, extensive research is required on the basic theory and nonlinear chaos technology in furnace heating, further improvements are needed in the minimum burn-up heating law and model, and the issue of inaccurate heating needs to be solved. Second, to address this problems of serious sputtering and short equipment life of molten pool melting furnace, the oxygen-enriched swirl chaotic stirring heating technology is developed to solve the problems of insufficient utilization of oxygen-enriched and insufficient self-heating and high energy consumption. Third, swirling chaotic combustion and heating system control technology should be developed to overcome issues with inaccurate heating and incomplete fuel combustion in the heating furnace. This will solve difficulties with uniformly heating metal workpieces, ensure heating quality, reduce energy consumption and achieve uniform and accurate heating.

(6) Construction and large-scale manufacturing technology of high-efficiency photovoltaic devices

Developing photovoltaic technology is as a vital and transformative initiative for harnessing renewable energy. To overcome the limitations of traditional silicon-based photovoltaic cells, various emerging thin-film photovoltaic technologies, such as cadmium telluride solar cells, copper indium gallium selenide-based solar cells, perovskite solar cells, and polymer solar cells, have come to the forefront of renewable energy. Recently, remarkable progress has been made for these photovoltaic technologies in both power conversion efficiency and large-scale manufacturing techniques. These advancements are important for enhancing their competitiveness and facilitating their commercialization. The unique advantages of these thin film photovoltaic technologies have significantly expanded the application horizons of photovoltaics, allowing for integration into urban infrastructure, consumer electronics, and beyond. These new applications include building integrated photovoltaics and portable devices. The future development of photovoltaic technology requires focused attention on the following four aspects. First, enhanced integration into new energy power systems to support the advancement of smart city construction. Second, integration with energy storage technology to achieve a steady supply and efficient utilization of green energy. Third, the recycling and reutilization of photovoltaic components to propel the industry towards green and sustainable growth. Fourth, pivotal technological breakthroughs for emerging photovoltaic technologies to reduce costs, extend the lifespan, and allow for successful mass production.

(7) Low-temperature and low-pressure thermal catalytic ammonia synthesis over a wide loading range

Ammonia, with an annual output of 180 million tons, plays an important role in modern agriculture and industry. Because of its easy liquefaction, high energy density, and zero carbon emissions, ammonia is called hydrogen 2.0 and is expected to become a next-generation energy carrier. Synthesis of NH_3 by the reaction of N_2 and H_2 is an exothermic process accompanied by a decrease in volume. A low temperature and high pressure are conducive for this reaction. However, because of the high bond energy and weak coordination ability of N_2 molecules, N_2 is difficult to activate at low temperatures. Currently, synthesis of ammonia is carried out continuously under the high temperature and high pressure, which has a high energy consumption and high carbon emissions. Additionally, clean energy, such as photovoltaics and wind, are volatile, retarding the green upgrades of traditional ammonia synthesis. Future development of low temperature and low-pressure green ammonia preparation technology with a wide loading range should focus on the following aspects: development of catalysts with high intrinsic activity, reduction of the adsorption energy barrier of N_2 on the catalyst surface, and improvement of the activation capacity of nitrogen at low temperature. In a traditional thermal catalytic reactor, electric, magnetic, and other external fields with variable frequency can be introduced to adjust the electronic structure of the active center of the catalyst to break the restrictions of adsorption and desorption. Devices and systems with rapid response abilities need to be developed to broaden the loading range of synthetic ammonia under low-temperature and low-pressure conditions.

(8) Development of ironmaking technology for hydrogen-rich carbon cycle blast furnaces

Blast furnace ironmaking is the main method for iron production currently. The global production of pig iron from blast furnaces exceeded 1.3 billion tons in 2022. The blast furnace–basic oxygen furnace (BF-BOF) process will still be an important method for iron and steel production in the future. Because approximately 2/3 of carbon emissions from iron and steel manufacturing comes from the blast furnace process, reducing carbon emissions from blast furnace ironmaking process is a focus of research in the global steel industry. The ironmaking technology for hydrogen-rich carbon cycle can minimize carbon emissions, by injecting hydrogen-rich gas (such as coke oven gas) into the blast furnace, which can replace the coke and coal, using the top gas recycling (TGR) technology and carbon capture, utilization and storage (CCUS) technology to reuse the CO and H_2, and capture CO_2 from blast furnace gas. The ironmaking technology for hydrogen-rich carbon cycle blast furnaces is the first choice for reducing carbon emission from traditional blast furnace because it does not need to change the process structures and charge structures. Companies such as Nippon Steel, ThyssenKrupp, and China Baowu are actively developing and experimenting the ironmaking technology for hydrogen-rich carbon cycle blast furnaces, and have achieved phased carbon reduction goals. The key points of ironmaking technology for hydrogen-rich carbon cycle blast furnaces include full-oxygen blast furnace iron-making technology, reheating and recycling of top gas after CO_2 capture, injection of hydrogen-enriched compound gases into the blast furnace, and self-circulation of the blast furnace gas under full-oxygen blast furnace conditions.

(9) Development and application of ultra-high energy density aluminum-air batteries

With the development of the global economy, energy demands have increased rapidly, which is of great concern. Currently, common traditional energy sources, such as lead-acid batteries, nickel-metal hydride batteries, and lithium-ion batteries, have limitations in their energy densities, safety, and production costs. Aluminum-air batteries (AABs) show potential as an energy storage system because of their high voltage (2.7 V), high capacity density (2 980 mAh/g), high energy density (8 100 Wh/kg), high safety, abundance of source materials, and environmentally friendly features. Research on the inhibition of hydrogen evolution on the anode surface has progressed in the key areas, such as alloying of anode materials, introduction of electrolyte additives, and use of organic electrolytes. The international community has established new goals for energy demand and technical indicators, and it is particularly important to design and develop AABs with ultra-high energy density, high safety, and high power that can be mass produced. Specifically, three key technological breakthroughs need to be achieved in the basic research and industrial applications of aluminum-air batteries in the future: ① development of battery modification technology (including anode alloying techniques and electrolyte additives) and understanding of the corresponding surface/interface reaction mechanism; ② development of a coupling model for battery components and subsequent optimization to simplify the battery structure and facilitate large-scale application; and ③ continuous development of AABs with low carbon emissions, high safety, and low cost, and utilization of the battery by-products to enhance the economic benefits of the AABs.

(10) Key preparation technologies and applications of high-purity metals, alloys, and materials

High-purity metals, alloys, and materials are mainly used in in semiconductor, wireless electronics, aerospace, and military fields, and in other cutting-edge science and technology. The methods for preparation of high purity materials include chemical purification and physical purification. Chemical methods mainly rely on the reactivity-selectivity principle of the chemical reaction, and impurities are removed through selective chemical reactions by modifying the reaction system, controlling the reaction conditions, and optimizing the reaction environment. In physical methods, similarities and differences in the physical characteristics of different elements are used to remove impurities through vacuum distillation, zone melting, and electromigration methods. Chemical and physical purification methods are usually combined to obtain highly purified materials. The core problems to be solved in the preparation of high purity metals, alloys and their materials include: ① the dispersion and distribution mechanism of impurity elements in materials; ② the similarity of elements and their selective separation kinetics, which are needed to calculate the interaction force, heat of absorption and desorption, and kinetic equilibrium parameters between the matrix and impurities; and ③ the mechanisms behind impurity phase morphology transformation, migration behavior, and the regulation of purification process parameters.

(11) Molecular design and large-scale preparation of new bio-aviation fuels

New bio-aviation fuels could be synthesized from biomass raw materials by precise chain breaking and re-synthesis through chemical bonding. Current research on new bio-aviation fuels focuses on four aspects. First, biofuel molecular design should be conducted by investigating the structure–activity relationship between the fuel molecular structure and physicochemical properties. Additionally, rational design and screening methods for high-throughput fuel molecules should be established, which could help to produce target molecule structure libraries from the molecular structure characteristics of the biomass raw materials. Second, an efficient and mild synthesis method is required to achieve high atom utilization for high output conversion of biomass feedstock to aviation fuel. Third, the mechanism of the catalytic reaction and the relationship between the catalyst structure and its performance in biomass conversion should be studied. This will guide the development of hyperdispersed low-load noble metal catalysts or non-noble metal catalysts with high activity and selectivity. Fourth, continuous improvement of catalysts and processes, development of integrated processes and optimization of reactor structures, improvement of the reaction efficiency, and reduction of the energy consumption are required for large-scale fuel preparation. There is an urgent demand for carbon emission reductions in the aviation field, and it is necessary to accelerate the pace of design, efficient synthesis, and large-scale preparation of bio-aviation fuel. New bio-aviation fuels that can replace petroleum-based aviation fuels will assist with this.

2.2 Interpretations for three key engineering development fronts

2.2.1 Metallurgical low-carbon utilization of renewable energy

The process of mining, smelting, and heat treatment in the steel and non-ferrous metallurgical industries directly consumes large quantities of fossil fuels. Implementation of clean energy substitutes is an effective measure to solve carbon emission problems. The green metallurgical industry need reconstruct the layout and overall arrangement, facilitate the transition of metallurgical production capacity to metal resources areas or renewable energy-rich areas of wind energy, solar energy, hydropower. For example, aluminum electrolysis companies can be constructed near nuclear power plants. Biomass energy, which has a mature manufacturing process but has always been limited in its application scale, is the only carbon-containing renewable energy source and is the best green and low-carbon alternative for metallurgical fuels and reducing agents. Exploring the efficient application of renewable energy in the metallurgical field is a new way to achieve green and low-carbon transformation of the metallurgical industry.

For steel metallurgy, the utilization of renewable energy has developed rapidly in recent years. Clean energy sources such as hydrogen energy, solar energy, wind energy, hydropower, and coal-to-gas conversion have been introduced. The use of multi-energy systems and complementary technologies has increased the use of clean energy in the metallurgical industry. New methods of energy recovery, such as waste heat utilization, have been developed, and cross-process and cross-industry energy recycling have been promoted by optimizing key processes and improving equipment. However, renewable energy has issues with intermittent instability, and it is difficult to achieve a continuous and stable energy supply. China has developed a relatively complete metallurgy system for steel hydrogen. As an example, the 1.2-million-ton hydrogen metallurgy demonstration project of the Hebei Province HBIS Group is the first in the world to use the coke oven gas self-reforming method to produce hydrogen. The obtained hydrogen has been used to directly reduce iron-containing raw materials and produce high-quality iron.

Development of green electricity in the non-ferrous metallurgical industry has been very rapid. For example, in Yunnan Province, China, which is rich in renewable energy, interest in electrolytic aluminum enterprises has increased. The scale of green aluminum and silicon production capacity in this region ranks among the top in the country, with an output value exceeding 100 billion RMB. Combination of silicon-aluminum industry with clean energy can realize the green development of integrated hydropower, silicon, and aluminum industries. However, the research and development and application of alternative technologies for biomass combustion and emissions reductions in the metallurgical industry are still in their infancy, and the future emission reduction potential is huge.

The relevant patents are mostly from China (Tables 2.2.1 and 2.2.2), which is consistent with its position as “the largest metallurgical country”. Kunming University of Science and Technology is ranked first in the number of patents because of its advantages of regional new energy resources and metallurgical technology research.

A roadmap for the next 20 years for the research front of “metallurgical low-carbon utilization of renewable energy” is shown in Figure 2.2.1. The main focuses are construction of a metallurgical energy system that combines multi-energy sources and energy storage systems to form a complementary clean energy supply system of wind, solar, water–hydrogen, and metallurgical waste heat and energy; development of a new technology for reduction of metallurgical slag by swirl injection of biomass fuel oil, and replacing fossil fuel energy reducing agents with renewable energy; and development of enhanced combustion technology for swirl atomization of biomass fuel oil and replacement of fossil fuels with renewable energy to achieve clean and low carbonization of metallurgical energy structure. The overall goal is transformation from carbon metallurgy to disruptive green low-carbon metallurgy in the next 10 years, and in the following 10 years reduction in the energy consumption of smelting and carbon emissions intensity. This will provide a metallurgical process with zero emissions.

Table 2.2.1 Countries with the greatest output of core patents on “metallurgical low-carbon utilization of renewable energy”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	513	98.65	218	97.76	0.42
2	India	2	0.38	0	0.00	0.00
3	Republic of Korea	2	0.38	0	0.00	0.00
4	Netherlands	1	0.19	5	2.24	5.00
5	Russia	1	0.19	0	0.00	0.00

Table 2.2.2 Institutions with the greatest output of core patents on "metallurgical low-carbon utilization of renewable energy"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Kunming University of Science and Technology	14	2.69	16	7.17	1.14
2	CISDI Engineering Company Limited	13	2.50	4	1.79	0.31
3	Jiangsu Binxin Iron and Steel Group Company Limited	7	1.35	1	0.45	0.14
4	Baoshan Iron & Steel Company Limited	6	1.15	2	0.90	0.33
5	Cangzhou China Railway Equipment Manufacturing Technology Company Limited	5	0.96	2	0.90	0.40
6	Yunnan Desheng Steel Company Limited	4	0.77	1	0.45	0.25
7	Wuhai Desheng Coal Coking Company Limited	4	0.77	0	0.00	0.00
8	Qingdao University of Technology	3	0.58	6	2.69	2.00
9	Xinhua Qunhua Ceramics Technology Company Limited	3	0.58	4	1.79	1.33
10	Angang Steel Company Limited	3	0.58	3	1.35	1.00

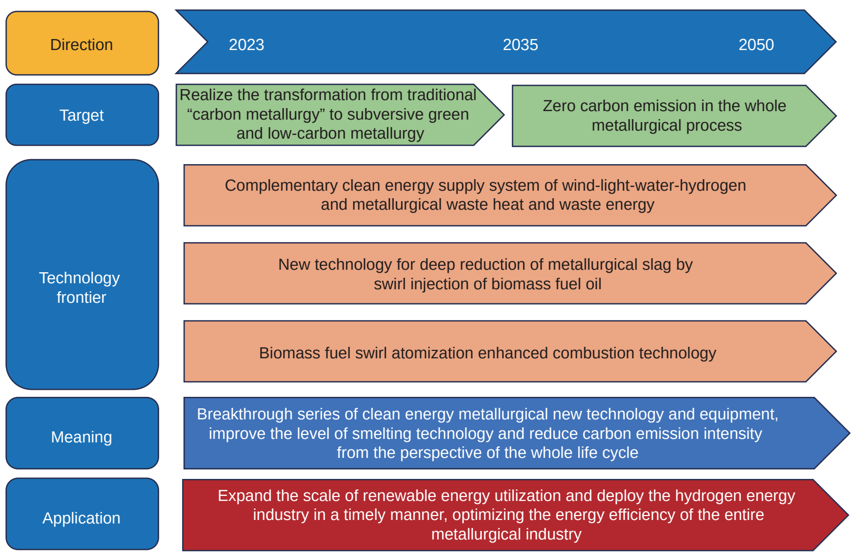

Figure 2.2.1 Roadmap of the engineering development front of "metallurgical low-carbon utilization of renewable energy"

2.2.2 Integration of large language models for the design and synthesis of advanced chemical engineering materials

The chemical and materials industry is a pillar of industrial society and forms the cornerstone of humanity's endeavor to explore and transform the material world. Each discovery and mass production of a new material signifies a leap forward. However, the traditional R&D paradigm of trial and error through experimentation and human summarization of patterns has reached its limits, which slows the design and preparation of new chemical materials. A paradigm shift is required in research methodologies. In the realm of new chemical materials, the data are characterized by large volumes yet sparse distributions. Relying on manual efforts or traditional models is inadequate to effectively unearth the patterns underlying the massive datasets. Large models offer the promise of integrating domain knowledge and tuning for specific material systems. This allows for a broad-to-specific technical trajectory to help scientists break from conventional thinking and accelerate material development.

As early as 2011, the USA took the lead by initiating the Materials Genome Initiative. China also launched a key project on the fundamental techniques and platforms for material genome engineering. With the continuous development of artificial intelligence, the number of patents geared towards the development of new chemical materials has been growing annually. China and the USA together account for over 70% of global patents in this field (Table 2.2.3), with the rest primarily originating from developed nations. Although the patent numbers are similar for China and the USA, the citation gap is significant, which suggests that the USA is the leader in this domain. Whereas patents from the USA are produced by both universities and enterprises, those from China are primarily produced by universities (Table 2.2.4). This highlights the need for China to catch up in terms of industry–academia–research integration. Moreover, China lags the USA in international collaboration and communication within this domain (Figure 2.2.2), and there is a need to further expand its global influence. Currently, this domain is a focus for international research, and the number of related patents published is increasing annually. According to the average citation count, this domain is at the forefront of developmental innovations. However, patents directly applying large models for material development remain scarce, which suggests that the field is still in its nascent stages and has vast potential for growth.

Table 2.2.3 Countries with the greatest output of core patents on "integration of large language models for the design and synthesis of advanced chemical engineering materials"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	180	37.34	877	64.77	4.87
2	China	177	36.72	337	24.89	1.90
3	India	33	6.85	0	0.00	0.00
4	Republic of Korea	24	4.98	33	2.44	1.38
5	Japan	21	4.36	24	1.77	1.14
6	UK	11	2.28	28	2.07	2.55
7	Germany	10	2.07	8	0.59	0.80
8	Canada	8	1.66	13	0.96	1.62
9	Australia	5	1.04	3	0.22	0.60
10	Switzerland	3	0.62	13	0.96	4.33

Table 2.2.4 Institutions with the greatest output of core patents on "integration of large language models for the design and synthesis of advanced chemical engineering materials"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	International Business Machines Corporation	14	2.90	34	2.51	2.43
2	Intel Corporation	8	1.66	35	2.58	4.38
3	Guangzhou University	8	1.66	2	0.15	0.25
4	Micron Technology Incorporated	7	1.45	0	0.00	0.00
5	Peptilogics Incorporated	6	1.24	14	1.03	2.33
6	Freenome Holdings Incorporated	6	1.24	13	0.96	2.17
7	University of California	6	1.24	7	0.52	1.17
8	Zhejiang University	5	1.04	10	0.74	2.00
9	Ro5 Incorporated	5	1.04	6	0.44	1.20
10	Stanford University	4	0.83	26	1.92	6.50

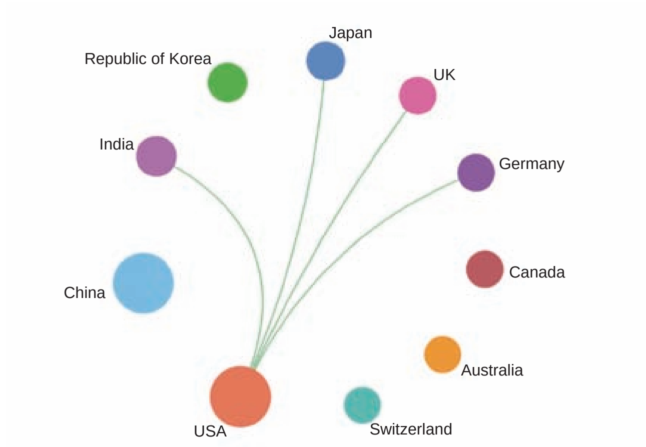

Figure 2.2.2 Collaboration network among major countries for the engineering development front of “integration of large language models for the design and synthesis of advanced chemical engineering materials”

In the next 5 to 10 years, large models are expected to aid multiple facets of the new chemical materials industry, accelerating design and preparation through literature information extraction, material structure generation, material property prediction, synthesis condition optimization, and intelligent characterization (Figure 2.2.3). First, literature information extraction is the main way to collect data for the chemical materials data platform. Large model is able to refine the extraction results of traditional models and output highly structured information so as to build a high-quality domain database. The creation of a high-quality domain-specific dataset and fine-tuning with domain knowledge are critical steps to optimize large model performance in this area. Second, large models that mine connections behind the data and formulate logical hypotheses could provide breakthroughs for material structure generation, which is vital for the reverse design of new materials. Generative models, a challenge in the artificial intelligence domain, are essential to enable artificial intelligence-driven scientific hypotheses. Third, material property prediction, which is a foundation for high-throughput screening, can be streamlined using large models that integrate various smaller models within the domain for precise predictions for various material properties. Integration of these smaller models into large models allows for discerning patterns by learning the parameters of the smaller models. Synthesis condition optimization and intelligent characterization are at the heart of exploring material fabrication techniques. Large models, with their superior

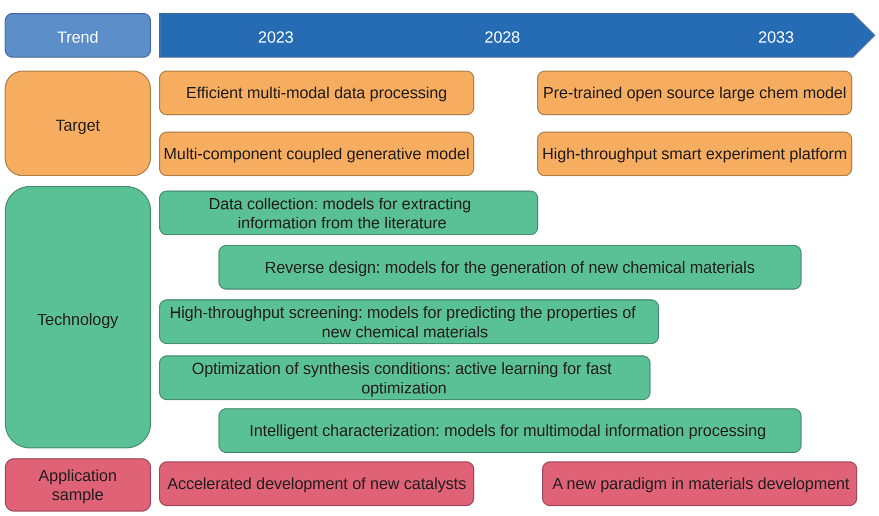

Figure 2.2.3 Roadmap of the engineering development front of “integration of large language models for the design and synthesis of advanced chemical engineering materials”

ability to discern patterns, can fully account for various influencing factors and swiftly optimize processes. Investigating multi-tiered active learning and establishing a universal framework in the chemical materials domain is crucial.

Taking polyolefin catalysts as an example, the chemical community currently relies on traditional methods for catalyst development. A single formula, from design and synthesis to characterization and final polymer evaluation, often takes several months, and most catalysts developed through this process do not meet final requirements. Leveraging the predictive abilities of large models can speed up the development of polyolefin catalysts. Further development of efficient high-end polyolefin catalysts could reduce the production costs of the key material, POE, used in photovoltaic industry encapsulation films. This will hasten the industrial production of domestic POE materials.

2.2.3 Design and preparation of metal matrix composites for high-temperature environments

Metal matrix composites (MMCs) are new materials made by adding inorganic non-metallic (or metallic) reinforcements of different sizes and morphologies (e.g., particles, fibers, whiskers, and nanosheets) to metals (e.g., aluminum, titanium, magnesium, and copper) using artificial methods. Compared with traditional homogeneous metals, MMCs have higher strength, corrosion resistance, electrical and thermal conductivity and other properties. They have broad application prospects in aerospace, national defense, rail transit, electronic information, and other fields. In the USA, particle-reinforced MMCs were first prepared by stir casting as early as the 1980s. In China, MMCs research began in 1981 and has already been applied in key components in many major projects. The field is currently in the stage of popularization and rapid development. Taking the aluminum matrix as an example, although it has high strength at room temperature, when used at 300–400 °C, this strength is eliminated. This mainly occurs because of the precipitation phase present in traditional high-strength aluminum alloys, which undergoes rapid destabilization and coarsening above 200 °C. Consequently, the material loses its strength, resulting in rapid softening and failure. The sharp decline in the mechanical properties of aluminum alloys in use is a key shortcoming that restricts structural design and affects the service safety, especially between 300 °C and 400 °C. This is of particular concern in the aerospace field. The 7075 aluminum alloy is widely used in aerospace and its tensile strength at 200 °C and 300 °C is only approximately 30% and 10% of that at room temperature, respectively. This hinders its effective use in heat-resistant structural components.

The principle behind thermal stability strengthening lies in the use of high thermal stability second-phase particles that pin grain boundaries, effectively hindering grain boundary slip and improving the stability of the matrix grain. At high temperatures, the load is transferred to the reinforcing particles through the interface, allowing for higher hardness of the reinforcing particles to bear a greater load and thereby enhancing the thermal stability of the material. For instance, Lavernia et al. successfully prepared a reinforced aluminum matrix composite containing TiC nanoparticles (35%) with tensile strength of up to 220 MPa and elongation of 10% at 300°C. However, it is worth noting that with further increases in the volume fraction of the reinforcement, the elongation greatly decreased. New materials with high strength-to-mass ratios at high temperatures, such as the high-strength 3D-printing aluminum alloy code-named Al250C developed by the WU Xinhua team in Australia, can have significant benefits in various applications. These materials, particularly MMCs, can be used to optimize thermal stability by adjusting and controlling the characteristics of the reinforcement particles and the interface between the reinforcement and the matrix. However, it is worth noting that the current tensile strength of aluminum matrix composites at 300 °C is generally below 250 MPa, and their plasticity and toughness are significantly lower than those of pure aluminum. Nevertheless, the improved performance, lightweight nature, and functionality of MMCs make them highly advantageous in many technological areas. Therefore, the design and preparation technology of MMCs in high-temperature environments are of great importance for enhancing scientific and technological strength, and particularly in achieving strategic goals.

Table 2.2.5 reveals the main countries that produce core patents in the engineering development front of "design and preparation of metal matrix composites for high temperature environments". Most of these patent outputs are from Asian countries, with China prominent in terms of patent disclosure and citation. There is some degree of international cooperation between China and the USA, while other countries and regions have not yet engaged in extensive collaboration (Figure 2.2.4). Notably, internationally relevant technologies are currently embargoed, particularly in the USA, where research reports in this field are predominantly concentrated in national laboratories, and the core technologies have not been made public yet. Major metal materials research institutions in China, such as the University of Science and Technology Beijing, Harbin Institute of Technology, and the Institute of Metal Research of the Chinese Academy of Sciences, have prioritized research and development of MMCs for high temperature environments (Table 2.2.6). In terms of enterprises, Wuxi Hengteli Metal Products and Anhui Nicola Electronic Technology are leaders, but there is no collaboration between the main institutions. The widespread distribution of research institutions also illustrates the significant research status and value of heat-resistant MMCs.

MMCs for high-temperature environments are facing an important period of strategic opportunity and are expected to be widely used in livelihood equipment in the next 5 to 10 years. Many foundational studies have been conducted on technology for the design and preparation of heat-resistant MMCs, but there are still many unsolved technical and scientific problems. Because of equipment replacement and technology upgrade requirements, research and development of heat-resistant MMCs is facing new challenges and demands. Breakthroughs are required for enhancing the heat-resistant limit temperature of the material, improving the stability of the material preparation, reducing the cost, and developing precision processing equipment and an evaluation system suitable for heat-resistant MMCs. To further promote the improvement and application of design theory and technology, several key aspects should be considered (Figure 2.2.5). First, biomimetic design should be conducted at the microstructural and morphological levels. Taking inspiration from the structural analysis of plants and animals

Table 2.2.5 Countries with the greatest output of core patents on “design and preparation of metal matrix composites for high-temperature environments”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	529	88.76	892	86.35	1.69
2	Japan	24	4.03	23	2.23	0.96
3	Republic of Korea	23	3.86	53	5.13	2.30
4	USA	9	1.51	56	5.42	6.22
5	India	4	0.67	1	0.10	0.25
6	Russia	2	0.34	2	0.19	1.00
7	Germany	2	0.34	0	0.00	0.00
8	Singapore	1	0.17	5	0.48	5.00
9	UK	1	0.17	4	0.39	4.00
10	Austria	1	0.17	0	0.00	0.00

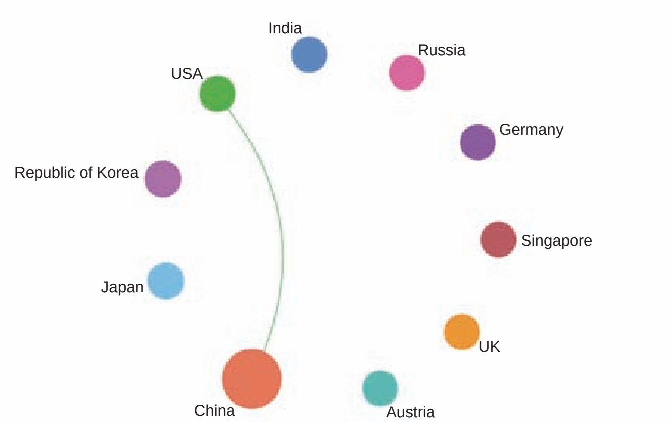

Figure 2.2.4 Collaboration network among major countries for the engineering development front of “design and preparation of metal matrix composites for high-temperature environments”

Table 2.2.6 Institutions with the greatest output of core patents on "design and preparation of metal matrix composites for high-temperature environments"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	University of Science and Technology Beijing	7	1.17	39	3.78	5.57
2	Harbin Institute of Technology	7	1.17	16	1.55	2.29
3	Institute of Metal Research Chinese Academy of Sciences	6	1.01	23	2.23	3.83
4	Wuxi Hengteli Metal Products Company Limited	6	1.01	5	0.48	0.83
5	Jilin University	5	0.84	35	3.39	7.00
6	Taiyuan University of Technology	5	0.84	11	1.06	2.20
7	Anhui Nigula Electronics Technology Company Limited	5	0.84	0	0.00	0.00
8	AVIC Manufacturing Technology Institute	4	0.67	46	4.45	11.50
9	Xi'an University of Technology	4	0.67	23	2.23	5.75
10	Zhejiang University	4	0.67	19	1.84	4.75

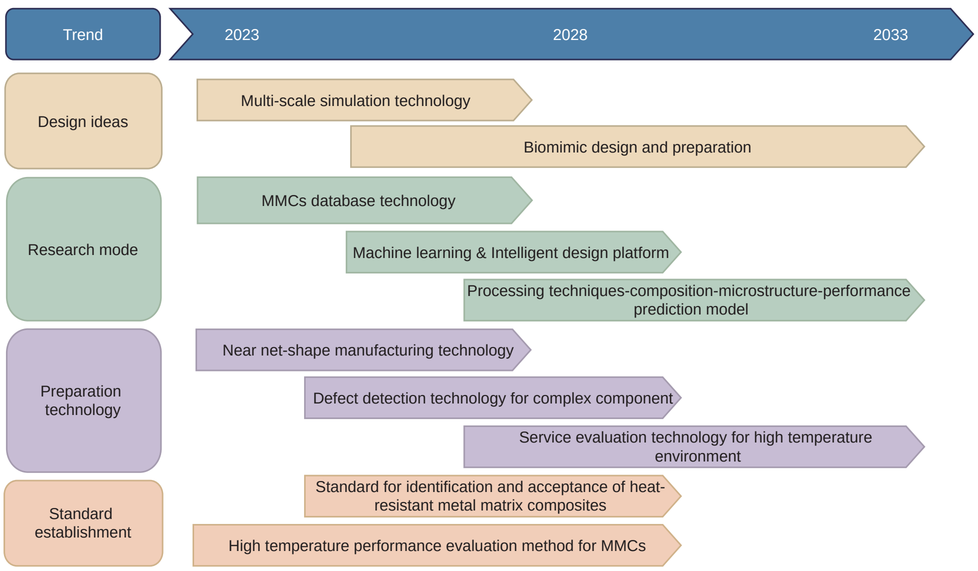

Figure 2.2.5 Roadmap of the engineering development front of "design and preparation of metal matrix composites for high-temperature environments"

residing in extreme environments, materials should be designed with a multi-scale approach from micro to macro. This design process could be further enhanced by developing a multi-scale computing platform that utilizes computational simulations to optimize the structural characteristics. Second, a new research paradigm should be established for genetic engineering of transitional materials. A multidimensional database could be constructed by exploring the physical and chemical properties of various materials such as metal oxides, carbides, nitride, borides, and nano-carbon,. This database, combined with simulation calculations of matrix composition, interface structure, and reinforcement distribution configuration, will facilitate the design and optimization of heat-resistant MMCs. Additionally, special near-net shape preparation and processing technology needs to be developed. This technology will address the technical challenges associated with processing MMCs, leading to improved utilization rates and formation accuracy for the materials. To achieve this, the technical prototype should be designed and improved according to the interface and reinforcement configuration of the MMCs. Furthermore, efficient forming technology, defect detection technology, and service evaluation technology for MMCs components with complex shapes should be developed. Finally, a comprehensive system of national and industry standards should be studied and established. This should include the establishment of high-temperature performance evaluation methods, identification criteria, and acceptance criteria for different sub-materials of MMCs used in high-temperature environments. The implementation of such a system will ensure standardized and reliable performance of these materials.

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IV. Energy and Mining Engineering

1 Engineering research fronts

1.1 Trends in Top 12 engineering research fronts

The Top 12 engineering research fronts as assessed by the Energy and Mining Engineering Group are shown in Table 1.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. Among these 12 research fronts, “research on direct hydrogen production from seawater”, “Power-to-X technologies based on renewable energy sources”, and “high-energy density lithium metal batteries” represent energy and electrical science, technology, and engineering research fronts; “mechanism of high temperature superconductor (HTS) material in compact fusion reactor” , “research on hydrogen production process route and critical material by nuclear energy”, and “critical technology in geological disposal of high-level radioactive waste” represent nuclear science, technology, and engineering research fronts; “detecting method of remote sensing image change for energy resources”, “drilling speed prediction model based on artificial neural networks”, and “characteristics and effects of reservoir stimulation in hydraulic fracturing” represent geology resources science, technology, and engineering research fronts; and “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”, “theoretical research on quality enhancement and efficiency improvement in the development of oil and gas in complex deepwater geological formations”, and “advancements in deep rock mechanics modeling for safe and efficient underground mining” represent research fronts of mining science, technology, and engineering.

The annual publication status of the core papers related to each frontier from 2017 to 2022 is shown in Table 1.1.2.

Table 1.1.1 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 direct hydrogen production from seawater	455	13 177	28.96	2020.8
2	Mechanism of high temperature superconductor (HTS) material in compact fusion reactor	468	4 595	9.82	2019.9
3	Detecting method of remote sensing image change for energy resources	36	2 342	65.06	2020.3
4	Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems	11	379	34.45	2021.5
5	Power-to-X technologies based on renewable energy sources	212	5 174	24.41	2020.4
6	High-energy density lithium metal batteries	282	75 243	266.82	2018.6
7	Research on hydrogen production process route and critical material by nuclear energy	174	15 263	87.72	2018.4
8	Critical technology in geological disposal of high-level radioactive waste	387	3 058	7.90	2020.0
9	Drilling speed prediction model based on artificial neural networks	42	686	16.33	2019.4
10	Characteristics and effects of reservoir stimulation in hydraulic fracturing	162	2 474	15.27	2019.9
11	Theoretical research on quality enhancement and efficiency improvement in the development of oil and gas in complex deepwater geological formations	114	783	6.87	2019.7
12	Advancements in deep rock mechanics modeling for safe and efficient underground mining	30	1 309	43.63	2020.0

Table 1.1.2 Annual number of core papers published for the Top 12 engineering research fronts in energy and mining engineering

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Research on direct hydrogen production from seawater	19	31	32	55	108	210
2	Mechanism of high temperature superconductor (HTS) material in compact fusion reactor	56	68	66	74	97	107
3	Detecting method of remote sensing image change for energy resources	1	0	7	11	14	3
4	Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems	0	0	0	0	6	5
5	Power-to-X technologies based on renewable energy sources	13	16	23	48	44	68
6	High-energy density lithium metal batteries	55	92	60	57	17	1
7	Research on hydrogen production process route and critical material by nuclear energy	52	46	44	21	7	4
8	Critical technology in geological disposal of high-level radioactive waste	55	42	51	58	71	110
9	Drilling speed prediction model based on artificial neural networks	1	5	8	4	9	10
10	Characteristics and effects of reservoir stimulation in hydraulic fracturing	12	28	29	32	24	37
11	Theoretical research on quality enhancement and efficiency improvement in the development of oil and gas in complex deepwater geological formations	16	20	11	25	21	21
12	Advancements in deep rock mechanics modeling for safe and efficient underground mining	1	3	6	7	10	3

(1) Research on direct hydrogen production from seawater

Direct hydrogen production from seawater is a technology that directly decomposes seawater into hydrogen and oxygen without pretreatment processes like desalination. However, due to the extremely complex composition of seawater (up to 92 chemical elements), it faces many challenges such as chlorination, membrane clogging and corrosion. Since the concept of direct seawater electrolysis was proposed in 1975, the four major paths of direct seawater electrolysis for hydrogen production have still been the main focus internationally for half a century. One is direct seawater electrolysis by developing catalysts, through improving electrochemical activity, introducing selective site or constructing protective coatings to avoid the competition between chlorination and oxygen precipitation reactions. The second is direct seawater electrolysis based on asymmetric electrolyte, which is achieved by adding a pure electrolyte at the anode side and seawater at the cathode side. The third is to isolate the purity ions via the hydrophilic reverse osmosis membrane. The last is seawater electrolysis based on physical mechanics, through the construction of a gas-liquid phase interface between seawater and electrolyte, and the use of the difference in saturated vapor pressure between the two as the mass transfer driving force, inducing the seawater in the form of gaseous water migration across the membrane to the electrolyte, completely isolating seawater ions and at the same time realizing the seawater without desalination process, side reactions, additional energy consumption of the seawater for the purpose of direct hydrogen production. The development of direct seawater electrolysis technology for hydrogen production will help promote the global emerging strategic industry of “offshore wind power and other renewable energy utilization—seawater hydrogen production”.

(2) Mechanism of high temperature superconductor (HTS) material in compact fusion reactor

Controlled fusion energy is an ideal clean energy resource for the future, and the most likely method for realizing controlled thermonuclear fusion at present is magnetic confinement fusion. Tokamak are considered to be the most promising magnetic confinement devices for realizing controlled nuclear fusion, and superconducting magnets are one of the key components of tokamak devices. Conventional tokamak devices use low-temperature superconducting magnets. In order to obtain a high fusion energy gain and fusion power density, the devices are often built very large, which increases the cost of the device. With the development of superconducting material technology, second-generation high-temperature superconducting materials have higher temperature margins, current densities, and critical magnetic fields compared to low-temperature superconducting materials. These characteristics promote the birth of more compact, higher magnetic field of high-temperature superconducting magnets. The breakthrough in high-temperature superconducting magnet technology has formed a new compact fusion reactor technology route, which not only greatly reduces the cost, but also dramatically shortens the research and development cycle. MIT Technology Review named the compact fusion reactor as one of the top ten breakthrough technologies in 2022. Internationally representative are the SPARC device from Massachusetts Institute of Technology (MIT) in the USA and the STEP device from Karam Fusion Energy Center in the UK, both of which are currently in the conceptual design stage.

(3) Detecting method of remote sensing image change for energy resources

Remote sensing imaging change detection is the use of multi-source remote sensing images and related geographic spatial data covering the same surface area at different times, in combination with corresponding features and remote sensing imaging mechanisms, in order to determine and analyze the changes in the features of the region through the image and graphic processing theory and mathematical modeling methods, including changes in the location and scope of the features, as well as changes in their properties and states.

In the initial stage, medium and low resolution remote sensing images were used. With the improvement of spatial resolution of remote sensing images, the differences in spatial texture representations of the same ground objects become larger, and the features of the ground objects become more complex and diverse. Traditional change detection methods are no longer sufficient to meet the needs. Hyperspectral image change detection and high-resolution image change detection have become important fields of change detection.

Modern information technologies such as remote sensing big data, the Internet, artificial intelligence (AI), and cloud computing are thriving, driving the rapid transformation and upgrading of remote sensing monitoring technology models. Utilization of existing data and computing resources, surface normalization and intelligent monitoring, and timely and efficient acquisition of land feature change information has become one of the current research hotspots. Future research trends include application scene change detection, construction and application of a dedicated sample set for large-scale change detection, and information mining of multi-source data.

(4) Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems

Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems study refers to the investigation of the thermal, hydrological, and mechanical interactions of rocks within geothermal systems by integrating multiple spatial and temporal scales. This simulation-based research aims to gain a deeper understanding of the impacts of geothermal energy extraction and subsurface water flow on geological fault zones and rock properties, with the ultimate goal of enhancing efficient geothermal resource development and environmental management.

The primary research directions are as follows: ① micro-scale research focuses on the microscopic characteristics of rock, including pore structure, mineral composition, thermal conductivity, and interactions between rocks and fluids; ② at the mesoscale, the research involves simulating the thermal-hydro-mechanical behavior of small-scale rocks, revealing relationships between fluid seepage, heat transfer, and mechanical responses within geothermal systems; and ③ macro-scale investigations explore the thermo-hydro-mechanical coupling behavior of rocks across the entire geothermal system, considering the influence of geological structures and groundwater flow on geothermal resources. Cross-scale simulations integrate information from different scales to provide comprehensive guidance for geothermal energy development.

With the advancement of computational capabilities and interdisciplinary collaboration, multiscale fractured simulation of the thermo-hydro-mechanical coupling processes in geothermal system rocks are expected to progress further. This will be reflected in ① more refined and efficient simulation methods utilizing new numerical algorithms, artificial intelligence, and other technologies to achieve more accurate simulation results; ② increased importance of data-driven simulation methods, optimizing numerical models utilizing real monitoring data to improve predictive accuracy, placing more emphasis on coupling effects, considering the mutual influences of factors such as temperature, pressure, and fluid transport; and ③ enhanced interdisciplinary cooperation, incorporating expertise from fields such as geology, hydrology, and geophysics into simulation studies.

(5) Power-to-X technologies based on renewable energy sources

Power-to-X technology is the use of green electricity generated from renewable energies (solar, wind, hydro, etc.) to produce green hydrogen, green methanol, green ammonia, and other products. This emerging technology can realize the transformation of intermittent renewable energies into storable chemical energy, thus contributing to the large-scale storage of renewable electricity. Meanwhile, Power-to-X enables linking renewable energies to industry, transportation, energy and power sectors. Therefore, it provides a suitable solution for the global economy decarbonization and for the provision of non-fossil fuel products.

At present, water electrolysis toward hydrogen is the key field of Power-to-X technology. Meanwhile, coupling green hydrogen with CO_2 and/or N_2 can provide a wealth of products. The direct conversion of H_2O with CO_2 and/or N_2 toward green methanol, green ammonia, and other products is also an active field of Power-to-X technolog. Of note, co-electrolysis of H_2O/CO_2 toward syngas, in combination with distributed micro-Fischer-Tropsch process holds a grand promise for generating carbon-neutral fuels and chemicals. Biomass and bio-derived platform molecules are one family of abundant renewable resources on earth with diverse molecular framework, active functional groups, and flexible molecular tailorability compared with CO_2 and N_2. Thus, it is a suitable object for green electricity processing. Moreover, biomass-based products are perfectly compatible with the economic system. Therefore, the Power-to-X technology coupled with biomass conversion has a great potential in carbon-neutral economy.

Breaking the key scientific and technological bottlenecks of the whole chain of material-electrode-electrolyzer-system, improving the energy conversion efficiency and the economic value of the products, and optimizing the linking method between the Power-to-X technology and the industrial, transportation and energy and power sectors is at the core of this grand topic.

(6) High-energy density lithium metal batteries

As an anode in second batteries, lithium (Li) metal has a very high theoretical specific capacity of 3 860 mAh/g and the lowest redox potential. Thus, it is the ultimate choice of anode material for high energy second batteries. In the 1970s attempts were made to use metallic Li as the anode in rechargeable batteries. However, it was found that Li dendrites were easily formed during charging (i.e., electrochemical deposition of Li), which could pierce the separator film and cause internal short-circuit, leading to thermal runaway and combustion explosion. In addition, Li dendrites could fracture to result in Li pulverization that will enhance the reactivity and safety risk. These fatal flaws block the commercialization of Li metal second batteries. Then, more attention was paid to Li+ intercalation anode materials. Finally, lithium-ion batteries based on graphite anodes entered the market in 1991. With the rapid development of electric vehicles and energy storage in the recent 10 years, second batteries with a higher energy density are demanded, and Li metal second batteries have come into sight again. Li-S battery and other new systems with an energy density above 400 Wh/kg have been intensively investigated. Nevertheless, two major problems of Li dendrite growth and low cycling efficiency related to Li metal anode still need to be solved. Optimization of the current collector structure, modification of the anode surface and use of Li metal composites can effectively suppress Li dendrite growth. Moreover, the electrochemical performance of Li metal anode is strongly dependent on the paired electrolytes. The optimization of liquid electrolyte compositions can improve the property of solid-electrolyte interphase layer, and in turn, suppress Li dendrite growth and enhance the Coulombic efficiency. In particular, the use of organic/inorganic composite electrolytes or inorganic electrolytes is expected to fundamentally solve the problems of Li metal anode. With the continuous emergence of new materials and the optimization of cell structures and charging mode, the practical application of Li metal second batteries might be realized.

(7) Research on hydrogen production process route and critical material by nuclear energy

As a secondary energy, hydrogen is an energy carrier or energy flow. The combination of nuclear energy and hydrogen energy will basically clean the whole process of energy production and utilization. The use of nuclear power to provide electricity for hydrogen production by electrolysis of water is one of the ways of hydrogen production by nuclear energy. At present, the main problem of hydrogen production from water electrolysis is the high energy consumption and low efficiency. If hydrogen production by electrolytic water in nuclear power is conducted during the low power consumption, the power grid resources can be rationally utilized and the cost of hydrogen production can be reduced. The high temperature generated by the nuclear fission process in the reactor has been extensively studied for direct use in thermal-chemical hydrogen production. Compared with hydrogen production by electrolytic water, the thermochemical process has a higher efficiency and a lower cost.

The principle and typical process of thermal-chemical hydrogen production is based on the thermochemical cycling, which catalyzes the thermal decomposition of water at 800–1 000 ℃ to produce hydrogen and oxygen. More than 100 thermochemical cycles have been developed. One of the keys to this method is to provide low-cost high-temperature heat sources. In recent years, the high temperature generated by nuclear fission in the reactor is an active research topic in the international nuclear engineering field, which may become a new application field of nuclear energy in the future. Hydrogen production by thermochemical process includes biomass thermochemical hydrogen production, thermochemical iodine-sulfur cycle hydrogen production, high temperature solid oxide electrolytic hydrogen production, methane (high temperature) reforming hydrogen production, of which the iodine-sulfur thermochemical cycle process is considered to be a more promising process. Thermal hydrogen production first requires the reactor to provide a high temperature of 750–1 000 ℃ . The cross-contamination of the nuclear system and the hydrogen production system during heat exchange must be prevented. The international roadmap for the 4th generation nuclear energy system (Gen IV) fully considers the issue of nuclear energy hydrogen production. In the recommended six nuclear energy systems, in addition to the very high temperature gas cooled reactor (VHGR) which mainly produces hydrogen, gas-cooled fast reactor (GFR), lead-cooled fast reactor (LFR), and molten-salt reactor (MSR) give consideration to both power generation and hydrogen production.

(8) Critical technology in geological disposal of high-level radioactive waste

High-level radioactive waste refers to the high-level waste liquid and its solidified body generated from the reprocessing of spent fuel in nuclear reactors. According to the classification of radioactive waste in China, high-level radioactive waste is divided into two categories: high-level liquid waste and high-level solid waste. High-level radioactive waste is a special waste that is highly radioactive, highly toxic, with long half-life nuclides and heat, which is extremely difficult to be safely dispose of, posing a series of scientific, technical, engineering, humanistic and sociological challenges. The internationally widely adopted feasible solution is deep geological disposal, that is, the high-level waste is buried in the geological body 500–1 000 m deep from the surface, so that it is permanently isolated from the human living environment. The underground works where high-level radioactive waste is buried are called “high-level radioactive waste disposal repositories”. Through the construction of an underground laboratory for high-level waste disposal, with the underground laboratory as a platform, many countries have determined the disposal site, developed a complete disposal theory and technical system, and entered the construction/preparation stage of the disposal repository. Finland received a permit for the construction of the repository in November 2015 and began construction in 2016; Sweden and France obtained permits for the construction of repositories; The USA allocated funds to restart the Yucca Mountain project in 2017. On May 6, 2019, with the consent of the State Council of the People’s Republic of China, the Bureau of Science, Technology and Industry for National Defense officially approved the underground laboratory construction project, which is a milestone for the geological disposal of high-level radioactive waste in China.

Major scientific issues to be addressed for the safe disposal of high-level waste include accurate prediction of the geological evolution of the disposal site, the characteristics of deep geological environment, the behavior of deep rock mass, groundwater and engineering materials under multi-field coupling conditions (medium-high temperature, ground stress, hydraulic action, chemical action and radiation action), the geochemical behavior of low-concentration transuranic radionuclides and their migration with groundwater, and the safety evaluation of disposal systems under ultra-long time scales, etc.

(9) Drilling speed prediction model based on artificial neural networks

The artificial intelligence-based drilling rate prediction model is a method that employs machine learning and data analysis techniques to forecast drilling rates in oil and gas drilling operations. This model analyzes various factors such as historical drilling data, geological information, drilling parameters, and applies artificial intelligence algorithms such as neural networks, decision trees, and support vector machines to construct a predictive model, providing decision-making support for drilling operation planning and optimization. Its research directions primarily encompass data collection, feature engineering, algorithm modeling, and model optimization. It requires the collection of a substantial amount of historical drilling data, extraction of features relevant to drilling rates, selection of appropriate algorithms for building predictive models, and iterative optimization to enhance accuracy and stability. With the continuous advancement of data technology and artificial intelligence, coupled with the increasing diversity and real-time nature of data, the gradual integration of information from other fields, and the application of automation technology, the model will become more accurate and reliable, offering real-time, comprehensive, and precise drilling rate prediction results.

(10) Characteristics and effects of reservoir stimulation in hydraulic fracturing

Hydraulic fracturing technology is the process of injecting fracturing fluid, which contains various additives, into the reservoir at a high pressure, utilizing the natural or induced fracture system of the reservoir. This process enlarges the fracture network of the reservoir and prevents the fractures from closing after the fracturing fluid is withdrawn, with the help of proppants such as sand or ceramic particles. As a result, the shale gas can continuously release and transport to the surface. China began studying the hydraulic fracturing technology in the 1950s. After years of exploration and reference, the first field test of hydraulic fracturing in shale gas wells was conducted in China from 2009 to 2011, marking the beginning of theoretical research and field application of shale gas fracturing. In 2012, Jiaoye 1 HF Well in Fuling Shale Gas Field achieved high production through hydraulic fracturing, indicating the localization of the fracturing technology in China. Since then, with the steady development of the fracturing technology, the total number of shale gas fracturing wells in China has reached 1 092 by 2020, and shale gas production has been increasing year by year. In 2020, the national shale gas production reached 200.4×10^8 m^3.

From the point of view of the total degree of reservoir reconstruction, the early implementation of the fracturing technology in China mainly includes the conventional staged multi-cluster fracturing technology, the synchronous fracturing technology, the zipper fracturing technology, the repeated fracturing technology, and so on. The staged multi-cluster fracturing technology is the leading technology of shale gas fracturing. With the in-depth development of shale gas development, to improve the transformation effect, especially the transformation volume and fracture network complexity of deep shale gas, the dense cluster forced sand fracturing technology has been developed since 2018. In the process of implementing this technology, to control the equilibrium degree of fractures, the temporary plugging fracturing technology and the non-uniform perforation fracturing technology have been developed to achieve adequate control of fracture extension uniformity.

(11) Theoretical research on quality enhancement and efficiency improvement in the development of oil and gas in complex deepwater geological formations

Generally, oil and gas resources in marine areas with a water depth exceeding 300 meters are generally classified as deepwater oil and gas. Deepwater oil and gas resources are abundant with significant potential, offering extensive prospects for exploration, development, and reservoir enhancement. Deepwater have emerged as a crucial replacement area for oil and gas reserves and production due to their substantial quantities. However, the lifespan of platforms limits deepwater oil and gas development, necessitating the achievement of stable and high production within a constrained timeframe. Quality enhancement and efficiency improvement of oil and gas development is urgently required. Over 70% of global oil and gas resources are located in the oceans, with 40% originating from deepwater sources. Of the 101 newly discovered large oil and gas fields in the past decade, 67% are deepwater fields accounting for 68% of the reserves. China's current deepwater oil and gas production has reached tens of millions of tons, marking significant progresses. Nevertheless, China's deepwater oil and gas exploration and development still remain in the preliminary stage. Complex reservoir origins, exploration, characterization, drilling and completion, and production challenges, coupled with heavy reliance on foreign materials and equipment, hinder further progress. Therefore, there is a pressing need to formulate theories for quality enhancement and efficiency improvement of oil and gas development in China’s complex deepwater geological formations. Key research areas include geological exploration methods, refined characterization techniques, safe drilling and completion technologies, research for supportive materials and equipment, and efficient production methods. Active exploration of novel approaches, development of new technologies, materials, and equipment, establishment of theoretical frameworks for quality enhancement and efficiency improvement of complex deepwater oil and gas development, and the formulation of scientifically reasonable development models hold the potential to significantly contribute to national energy security.

(12) Advancements in deep rock mechanics modeling for safe and efficient underground mining

Advancements in deep rock mechanics modeling for safe and efficient underground mining refers to the application of advanced mechanical models and numerical simulation techniques to study the mechanical behaviors of rocks, such as deformation, fracturing, and stress distribution, in deep underground mining, in order to predict and assess geological hazards like rock instability and collapses that might occur. This research provides scientific guidance for safe and efficient mining practices.

In the domain of safe and efficient deep underground mining rock mechanics modeling, the main research directions encompass the following vital areas: ① constitutive modeling of rocks explores the deformation characteristics of different rock types under extreme conditions like high pressure and temperature, providing accurate numerical descriptions of rock deformation behaviors during mining; ② studies on mechanical behavior of porous rock masses concern the influence of groundwater flow on rock mechanics and the response of rock-water coupling within porous media during extraction; and ③ studies on multiscale modeling utilize cross-scale simulations to reveal rock mechanics responses from micro to macro scales.

With the rapid advancement of the computer technology, rock mechanics modeling for safe and efficient deep underground mining is becoming more refined and accurate. This will be reflected in: ① models considering nonlinearities, anisotropy, and damage characteristics of rocks in greater detail to enhance simulation accuracy; ② deeper investigations into coupling effects, encompassing factors such as groundwater flow, temperature, and stress in simulations, leading to more comprehensive predictions of rock mechanics responses; and ③ increased application of artificial intelligence and machine learning techniques for optimizing model parameters, accelerating simulation processes, and improving simulation efficiency. As the depth of deep mining operations increases, rock mechanics modeling will also focus on studying mechanical behaviors at even deeper underground levels.

1.2 Interpretations for four key engineering research fronts

1.2.1 Research on direct hydrogen production from seawater

Water electrolysis highly relies on freshwater resources, while the shortage of freshwater resources seriously restricts the development of hydrogen production. Ocean is the largest hydrogen source on earth, and obtaining sea water to produce “green hydrogen” is an important strategic direction for future scientific and industrial development. However, the composition of seawater is extremely complex, involving 92 chemical elements, many microorganisms, solid impurities, etc. Its lower conductivity and large fluctuations easily lead to side reactions, catalyst deactivation, and membrane clogging, and other issues in the electrolysis process, which poses a great challenge to the high performance, stability, high efficiency, and compatibility of the electrolysis system.

Desalination followed by hydrogen production is the most mature seawater hydrogen production technology path and has been conducted in China and abroad in large-scale demonstration projects. However, this type of technology relies heavily on large-scale desalination equipment, and the process is complex and occupies a large amount of land resources, which further pushes up the cost of hydrogen production and the difficulty of engineering construction. Since the concept of direct seawater hydrogen production was proposed in 1975, the four major paths of direct seawater electrolysis for hydrogen production have still been the main focus internationally for half a century. Of the four major paths, catalyst engineering is currently the most traditional and conventional way to solve the challenge of seawater hydrogen production, mainly through the improvement of electrochemical activity, the introduction of selective sites, and the construction of protective coatings to avoid the competition between chlorination and oxygen precipitation reactions. The second path is direct hydrogen production from seawater based on asymmetric electrolyte, which is achieved by adding a single, pure electrolyte at the anode side and seawater at the cathode side. The third path is based on membrane isolation, which excludes impurity ions in seawater by utilizing the in-situ membrane screening method of hydrophilic reverse osmosis. The last path is based on the phase change migration of physical mechanics, through the construction of a gas-liquid phase interface between seawater and electrolyte, and the use of the difference in saturated vapor pressure between the two as the mass transfer driving force, inducing the seawater in the form of gaseous water migration across the membrane to the electrolyte, completely isolating seawater ions and at the same time realizing direct hydrogen production without the desalination process, side reactions, additional energy consumption of seawater. This pathway has been validated in the world’s first offshore wind power seawater direct electrolysis hydrogen production sea trial on May 27, 2023 in Xinghua Bay, Fujian Province in China.

In the engineering research front of “research on direct hydrogen production from seawater”, the countries with the highest publication of core papers and the average citations per paper are China and the USA, respectively (Table 1.2.1), and there are lots of collaborations among China, the USA, and Australia (Figure 1.2.1). In the top ten institutions in terms of the number of papers published, Chinese Academy of Sciences and Qingdao University of Science and Technology rank top two, and the institutions with the highest citations per paper are University of Houston and Tianjin University (Table 1.2.2). There are many collaborations between China University of Petroleum (East China), Qingdao University of Science and Technology, Shenzhen University, and Zhengzhou University (Figure 1.2.2). Countries and institutions with the greatest output of citing papers are shown in Tables 1.2.3 and 1.2.4.

At present, the phase change migration of seawater direct electrolysis hydrogen production technology route has begun to take advantage, is expected to realize 100 Nm^3/h H_2 seawater hydrogen production system mass production by 2025, before 2028 to realize 1 000–3 000 Nm^3/h H_2 seawater hydrogen system mass production, before 2033 to realize the application scenario to the sewage, wastewater, and other non-pure water resources of the direct production of hydrogen on a large scale (Figure 1.2.3). Countries and institutions with the greatest output of citing papers are shown as Tables 1.2.3 and 1.2.4.

Table 1.2.1 Countries with the greatest output of core papers on “research on direct hydrogen production from seawater”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	249	54.73	7 803	31.34	2021.3
2	USA	79	17.36	3 432	43.44	2020.5
3	Republic of Korea	31	6.81	584	18.84	2021.0
4	Australia	25	5.49	1 162	46.48	2020.7
5	Japan	23	5.05	280	12.17	2020.2
6	UK	19	4.18	223	11.74	2020.7
7	Germany	15	3.30	939	62.60	2019.7
8	Canada	15	3.30	566	37.73	2020.5
9	India	15	3.30	262	17.47	2021.1
10	Netherlands	12	2.64	516	43.00	2020.3

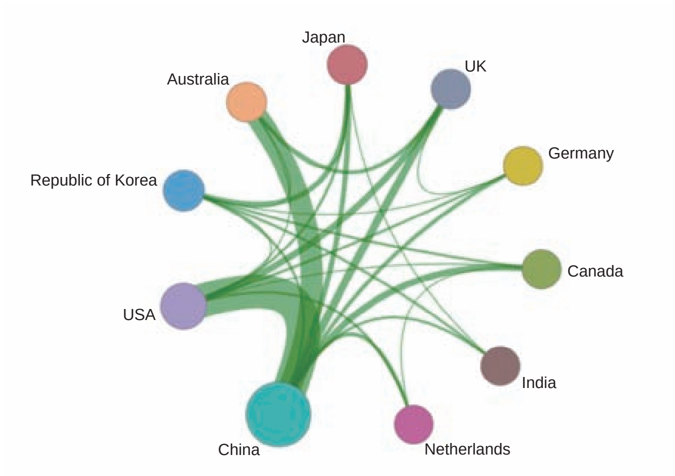

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "research on direct hydrogen production from seawater"

Table 1.2.2 Institutions with the greatest output of core papers on "research on direct hydrogen production from seawater"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	28	6.15	632	22.57	2021.0
2	Qingdao University of Science and Technology	27	5.93	318	11.78	2021.8
3	Wuhan University of Technology	17	3.74	435	25.59	2021.5
4	University of Houston	12	2.64	1 703	141.92	2021.0
5	China University of Petroleum (East China)	11	2.42	244	22.18	2021.5
6	Nankai University	11	2.42	213	19.36	2021.5
7	Tianjin University	10	2.20	467	46.70	2020.9
8	Shenzhen University	10	2.20	198	19.80	2021.4
9	Zhengzhou University	9	1.98	155	17.22	2021.8
10	University of Shanghai for Science and Technology	9	1.98	60	6.67	2021.7

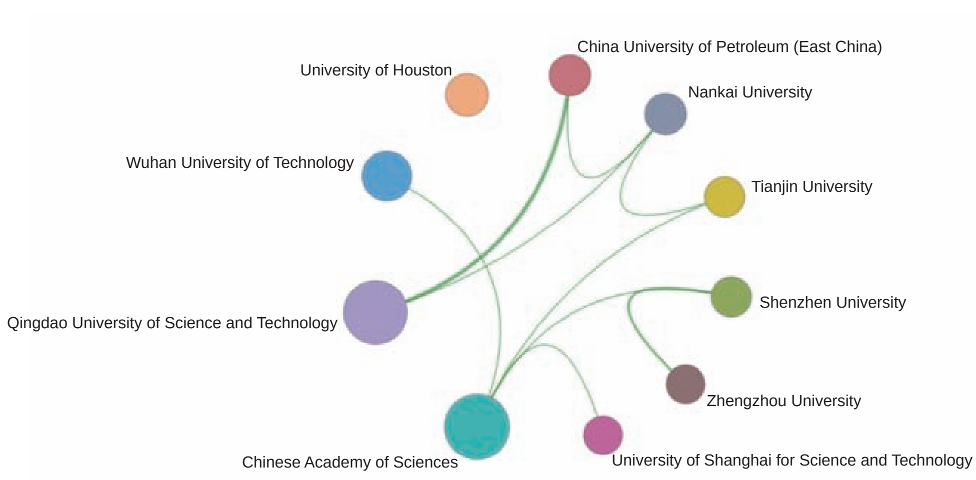

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "research on direct hydrogen production from seawater"

Table 1.2.3 Countries with the greatest output of citing papers on "research on direct hydrogen production from seawater"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	561	57.54	2020.4
2	USA	119	12.21	2020.0
3	Australia	56	5.74	2020.3
4	Republic of Korea	54	5.54	2020.3
5	Germany	35	3.59	2020.3
6	UK	33	3.38	2020.4
7	Singapore	28	2.87	2020.2
8	Japan	25	2.56	2020.3
9	Iran	23	2.36	2019.8
10	Canada	22	2.26	2020.4

Table 1.2.4 Institutions with the greatest output of citing papers on "research on direct hydrogen production from seawater"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	77	26.55	2020.1
2	Soochow University	27	9.31	2020.0
3	Tsinghua University	24	8.28	2020.5
4	Hunan University	24	8.28	2020.4
5	Zhengzhou University	23	7.93	2020.6
6	Tianjin University	21	7.24	2020.3
7	Wuhan University of Technology	21	7.24	2020.4
8	Beijing University of Chemical Technology	19	6.55	2020.3
9	University of Science and Technology of China	18	6.21	2020.4
10	Qingdao University of Science and Technology	18	6.21	2020.4

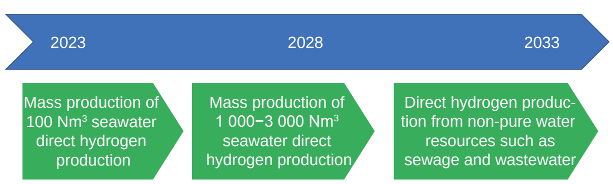

Figure 1.2.3 Roadmap of the engineering research front of "research on direct hydrogen production from seawater"

1.2.2 Mechanism of high temperature superconductor (HTS) material in compact fusion reactor

Fusion energy is clean, safe, and relatively abundant, which is the ideal energy source that is most likely to fundamentally solve the future energy crisis. Tokamak devices are considered to be the most promising magnetic confinement devices for the realization of controlled nuclear fusion. A superconducting magnet is one of the key components of a tokamak device, providing the poleward and ringward magnetic fields that generate and confine the plasma to realize fusion. In tokamak devices, the fusion energy gain and fusion power density have a scalar relationship with the toroidal magnetic field, and the central toroidal magnetic field of magnets utilizing traditional low-temperature superconducting materials can only reach about 7 T, such as the EAST of China, the JT-60SA of Japan, the JET of the UK, and the International Thermonuclear Experimental Reactor (ITER) of international cooperation. With the development of superconducting material technology, the second generation high-temperature superconducting materials have higher temperature margins, current densities, and critical magnetic fields compared to low-temperature superconducting materials. These properties have led to the creation of more compact high-temperature superconducting magnets with higher magnetic fields. Since the cost of a tokamak device is approximately cubic to the large radius of the device, the high-temperature superconducting magnet technology can effectively reduce the overall cost of the fusion device, which plays an important role in further promoting the application of fusion energy in the future. At present, British Tokamak Energy has completed the preparation of the ST25-HTS device, which confirms the feasibility of combining tokamak and high-temperature superconducting materials. In the next five years, MIT plans to use high-temperature superconducting materials to complete a SPARC demonstration device with a center ring magnetic field greater than 12 T, a power gain coefficient Q greater than 2, and a fusion energy greater than 50 MW. Compact high-temperature superconducting tokamak utilizing high-temperature superconducting magnets has become an important research direction for future controlled fusion technology.

In the research front of “mechanism of high temperature superconductor (HTS) material in compact fusion reactor”, the top three countries in terms of the number of core papers published are China, the USA, and Japan. The top three countries in terms of the citations per paper are the USA, Republic of Korea, Switzerland, and Russia (Table 1.2.5). In the top ten countries, China has more cooperation with the USA, and Germany has more cooperation with Switzerland (Figure 1.2.4). In the top ten institutions in terms of the number core paper published, Chinese Academy of Sciences, University of Science and Technology of China, and MIT are the top three, and the top three institutions with the highest citations per paper are MIT, University of Colorado, and Princeton Plasma Physics Laboratory (Table 1.2.6). In the top ten institutions, there are more collaborations between Chinese Academy of Sciences and University of Science and Technology of China (USTC), and more collaborations between the National Institute for Fusion Science (NIFS) and Tohoku University (Tohoku, Japan) (Figure 1.2.5). The main output

Table 1.2.5 Countries with the greatest output of core papers on “mechanism of high temperature superconductor (HTS) material in compact fusion reactor”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	130	27.78	959	7.38	2020.0
2	USA	116	24.79	2 238	19.29	2019.9
3	Japan	72	15.38	994	13.81	2019.6
4	Germany	44	9.40	565	12.84	2019.7
5	Italy	41	8.76	379	9.24	2020.0
6	Switzerland	40	8.55	677	16.93	2020.0
7	UK	30	6.41	350	11.67	2020.2
8	Republic of Korea	25	5.34	456	18.24	2019.5
9	France	22	4.70	271	12.32	2019.5
10	Russia	18	3.85	301	16.72	2019.8

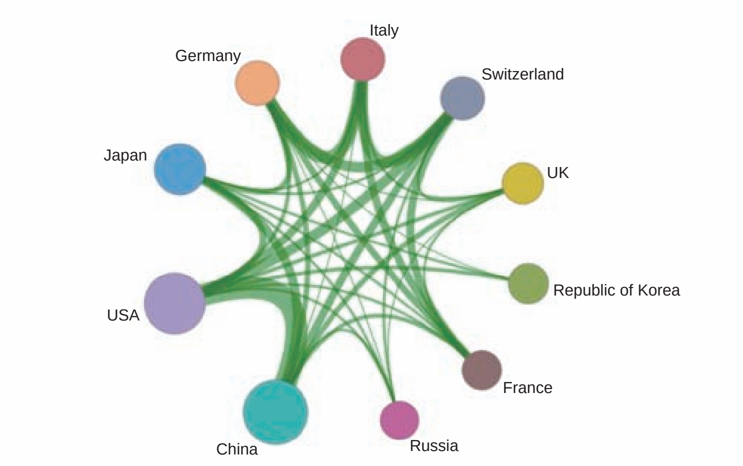

Figure 1.2.4 Collaboration network among major countries in the engineering research front of "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

Table 1.2.6 Institutions with the greatest output of core papers on "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	87	18.59	517	5.94	2020.0
2	University of Science and Technology of China	42	8.97	234	5.57	2020.2
3	Massachusetts Institute of Technology	29	6.20	1003	34.59	2019.6
4	National Institute for Fusion Science	27	5.77	173	6.41	2019.9
5	Tohoku University	22	4.70	204	9.27	2019.3
6	Politecnico di Torino	20	4.27	195	9.75	2020.1
7	Karlsruhe Institute of Technology	20	4.27	178	8.90	2019.7
8	Princeton Plasma Physics Laboratory	19	4.06	249	13.11	2020.0
9	Lawrence Berkeley National Laboratory	17	3.63	75	4.41	2020.8
10	University of Colorado	15	3.21	265	17.67	2020.9

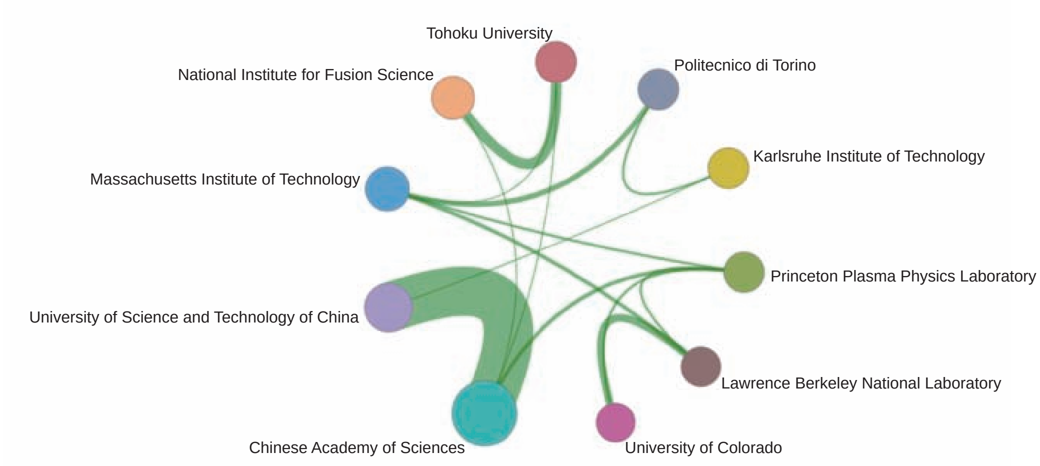

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

countries of citing papers are China and the USA (Table 1.2.7), and the main output institutions of citing papers are Chinese Academy of Sciences, the USTC, and MIT (Table 1.2.8).

In the next ten years, compact fusion reactors built on an international scale utilizing high-temperature superconducting magnets include the SPARC device of MIT, a small-scale version of the planned fusion power plant. The successful operation of SPARC will prove that a full-scale commercially operated fusion power plant is feasible, and can be expected to be a zero-emission, unlimited energy source, clearing the way for the rapid design and construction of commercially available, controllable fusion power stations, clearing the way for the rapid design and construction of a commercial controllable fusion power plant, making fusion power the centerpiece of future clean energy and changing the future energy landscape of the world. After completing the feasibility study on the application of high-temperature superconducting fusion reactors, the construction of high-temperature superconducting fusion power stations will be conducted to realize fusion power generation (Figure 1.2.6).

Table 1.2.7 Countries with the greatest output of citing papers on "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 120	29.11	2021.0
2	USA	828	21.52	2020.8
3	Japan	372	9.67	2020.7
4	Germany	332	8.63	2020.7
5	UK	246	6.39	2021.0
6	Italy	224	5.82	2020.9
7	Republic of Korea	166	4.32	2021.0
8	France	161	4.19	2020.8
9	Switzerland	150	3.90	2020.9
10	Russia	145	3.77	2021.1

Table 1.2.8 Institutions with the greatest output of citing papers on "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	385	32.06	2021.1
2	University of Science and Technology of China	153	12.74	2021.0
3	Massachusetts Institute of Technology	129	10.74	2020.6
4	Shanghai Jiao Tong University	86	7.16	2021.0
5	Oak Ridge National Laboratory	82	6.83	2020.8
6	National Institute for Fusion Science	68	5.66	2020.4
7	Lanzhou University	64	5.33	2021.3
8	Karlsruhe Institute of Technology	61	5.08	2020.4
9	Tsinghua University	61	5.08	2020.6
10	Seoul National University	57	4.75	2021.0

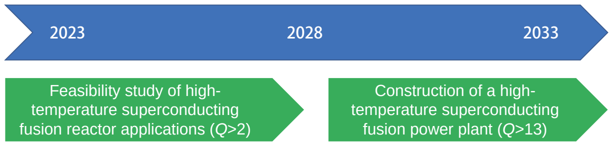

Figure 1.2.6 Roadmap of the engineering research front of "mechanism of high temperature superconductor (HTS) material in compact fusion reactor"

1.2.3 Detecting method of remote sensing image change for energy resources

Change detection is an important direction in the research of remote sensing image processing and analysis methods. The core is to use remote sensing images from different periods at the same region to analyze the change status and correlation of land features. The utilization of remote sensing spectral information has undergone a process from black and white panchromatic images to multispectral, hyperspectral, and time series, while the change detection methods have also evolved from pixel based algebraic calculations to machine learning algorithms and multi method joint algorithms. For example, the traditional methods are to use time series for change detection, including classification, threshold, image transformation, model, etc. In recent years, with the continuous launch of remote sensing satellites equipped with high spatial resolution optical cameras and the widespread application of mobile and flexible drone remote sensing, the number, detection accuracy, and information integrity of remote sensing images have continuously improved. The frequency of obtaining data for the same area has also gradually increased, providing an important foundation for remote sensing image change detection. In this context, the "artificial intelligence plus remote sensing big data" model has become a common consensus in the construction of industry application systems in recent years. The main research directions include the effective extraction of joint features of "time space spectrum" in multi temporal hyperspectral images, high-precision change detection and calculation methods based on deep learning, and so on. High-precision and automated change detection methods have important practical and strategic significance for mineral resource exploration, national ecological environment protection, and marine environmental monitoring.

The International Society of Photogrammetry and Remote Sensing has established a separate working group for change detection for remote sensing imagery research for many years, dedicated to promoting the development of multi-field change detection utilizing the remote sensing technology. The U.S. National Geospatial-Intelligence Agency has also incorporated change detection for remote sensing imagery detection and analysis into strategic planning. China has also attached great importance to the application of the remote sensing change detection technology in the detection of geographical conditions. Since 2010, the Ministry of Land and Resources has been conducting national remote sensing detection work every year, utilizing change detection for multi-temporal remote sensing imagery technology to continuously update national land survey results.

In the engineering research front of "detecting method of remote sensing image change for energy resources", the main producing country of core papers is China (35), accounting for 97.22% of the total, while other countries account for less than 10%. Italy (3) ranks second, accounting for 8.33% (Table 1.2.9). In terms of the main producing institutions of core papers (Table 1.2.10), China accounts for 8 of the Top 10 institutions. Among them, Wuhan University (13), Chinese Academy of Sciences (6), and Beihang University (4) rank top three. China (777) is also the main producer of citing papers, accounting for 67.80% of the total. The USA (82) ranks second, only accounting for 7.16% (Table 1.2.11). The top three major producing institutions for citing core papers are Wuhan University (125), Chinese Academy of Sciences (116), and Xi'an University (39) (Table 1.2.12). Cooperation in this field is dominated by China, with Italy, the USA, the Netherlands and other countries cooperating around China (Figure 1.2.7). Collaborative research between institutions is concentrated at Wuhan University, Chinese Academy of Sciences, Beihang University, Nanjing University of Information Science and Technology, and Central South University (Figure 1.2.8).

In the next 5–10 years, the detecting methods of remote sensing imaging change for energy resources will usher in a series of important development (Figure 1.2.9). The fusion of high-resolution and multi-spectral data will provide more accurate detection capabilities for resource change, including the application of the multi-source data fusion and hyperspectral technology. In addition, the popularization of machine learning and deep learning technologies will automate the analysis of remote sensing data and reduce the degree of manual intervention. Moreover, time-series data analysis will help better understand the trend and periodicity of resource change, and improve detection accuracy. The use of cloud computing and distributed computing resources will also increase the efficiency of data processing and analysis. These methods will play a key role not only in environmental monitoring, resource management, and climate change research, but also in areas such as smart city planning, sustainable development, precision agriculture, and forest resource management. With continuous development, the application of these detection methods for energy resources will become more extensive, providing more powerful tools for decision-making support and resource management.

Table 1.2.9 Countries with the greatest output of core papers on "detecting method of remote sensing image change for energy resources"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	35	97.22	2 330	66.57	2020.3
2	Italy	3	8.33	193	64.33	2020.7
3	Netherlands	2	5.56	398	199.00	2019.5
4	Germany	2	5.56	54	27.00	2020.0
5	Australia	2	5.56	47	23.50	2020.5
6	USA	1	2.78	20	20.00	2020.0
7	UK	1	2.78	15	15.00	2021.0

Table 1.2.10 Institutions with the greatest output of core papers on "detecting method of remote sensing image change for energy resources"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Wuhan University	13	36.11	1 153	88.69	2020.1
2	Chinese Academy of Sciences	6	16.67	432	72.00	2019.2
3	Beihang University	4	11.11	312	78.00	2020.8
4	Nanjing University of Information Science and Technology	3	8.33	256	85.33	2020.3
5	Central South University	3	8.33	179	59.67	2021.0
6	Utrecht University	2	5.56	398	199.00	2019.5
7	China University of Mining and Technology	2	5.56	138	69.00	2020.0
8	Southwest Jiaotong University	2	5.56	75	37.50	2021.0
9	University of Trento	2	5.56	63	31.50	2021.0
10	Beijing Normal University	2	5.56	28	14.00	2021.0

Table 1.2.11 Countries with the greatest output of citing papers on "detecting method of remote sensing image change for energy resources"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	777	67.80	2021.3
2	USA	82	7.16	2021.1
3	Italy	42	3.66	2021.3
4	Germany	41	3.58	2021.1
5	Republic of Korea	38	3.32	2021.0
6	Canada	35	3.05	2021.3
7	UK	34	2.97	2021.3
8	Netherlands	27	2.36	2020.7
9	India	26	2.27	2021.5
10	France	25	2.18	2020.7

Table 1.2.12 Institutions with the greatest output of citing papers on "detecting method of remote sensing image change for energy resources"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Wuhan University	125	26.54	2021.1
2	Chinese Academy of Sciences	116	24.63	2021.2
3	Xidian University	39	8.28	2021.1
4	China University of Geosciences	31	6.58	2021.4
5	Nanjing University of Information Science and Technology	30	6.37	2021.1
6	Sun Yat-sen University	27	5.73	2021.2
7	Northwestern Polytechnical University	23	4.88	2021.1
8	University Trento	23	4.88	2021.1
9	Beihang University	20	4.25	2021.2
10	German Aerospace Center (DLR)	19	4.03	2021.2

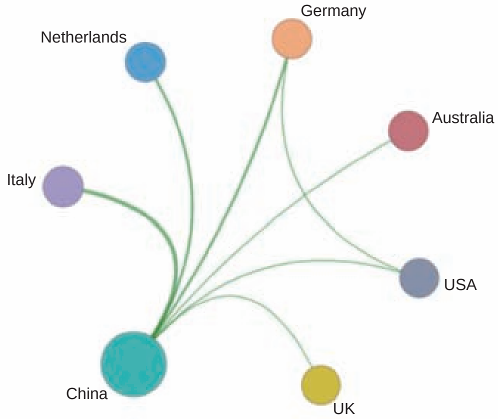

Figure 1.2.7 Collaboration network among major countries in the engineering research front of "detecting method of remote sensing image change for energy resources"

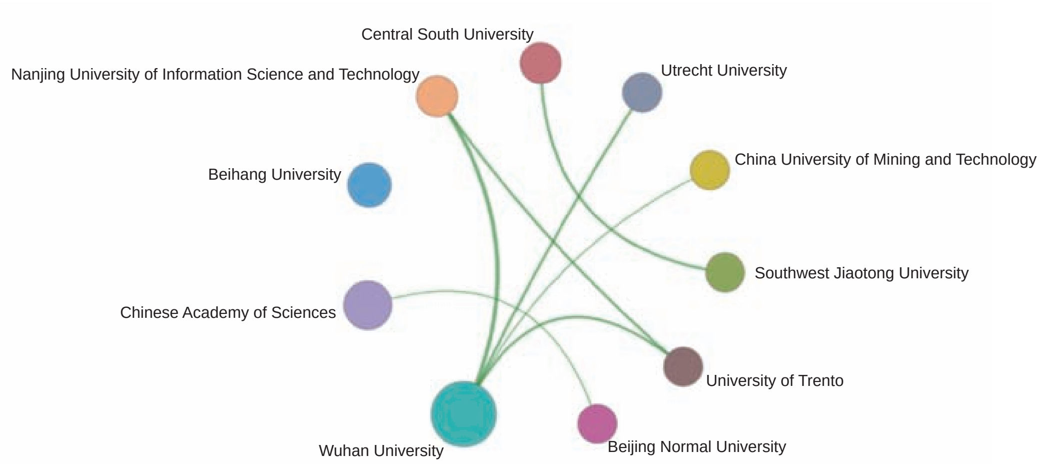

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “detecting method of remote sensing image change for energy resources”

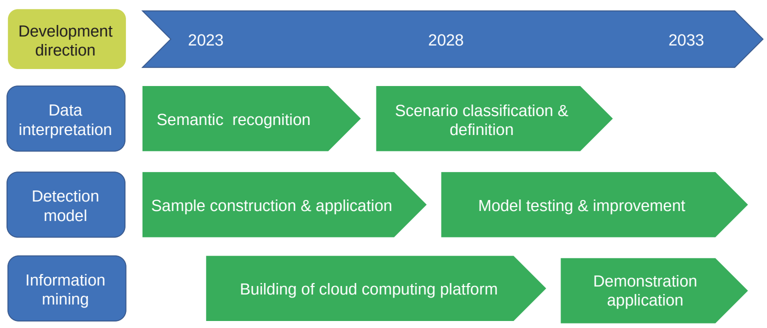

Figure 1.2.9 Roadmap of the engineering research front of “detecting method of remote sensing image change for energy resources”

1.2.4 Multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems

Multiscale fractured modeling and simulation of coupled thermo-hydro mechanical processes in rocks for geothermal systems is a pivotal forefront in the interaction between geothermal energy utilization and geological environment. The research in this field aims to deeply understand the thermal, hydrological, and mechanical coupling behaviors of rocks within geothermal systems, providing a scientific foundation for geothermal resource development and management. Over the past few decades, significant progress has been made in this field due to advancements in numerical simulation, computational capabilities, and data monitoring technologies.

The history of research into the thermal-hydro mechanical coupled processes in fracture rocks for geothermal system can be traced back to the 1980s. Initially, the research mainly focused on single-scale experiments and theoretical models, exploring relationships between elements such as temperature, pressure, and water flow within geothermal systems. With the development of experimental equipment and computer technology, multiscale fractured experiments and simulation methods gradually came into play, enabling researchers to more comprehensively unveil the complex coupling behaviors of geothermal systems. In recent years, with the growing attention paid to deep geothermal resources, multiscale fractured simulation research has gained more significance in predicting and addressing challenges in geothermal energy development.

The thermal-hydro mechanical coupled behavior in geothermal systems profoundly impacts the efficiency and sustainability of geothermal energy utilization. Understanding the physical and chemical responses of rocks aids in optimizing geothermal energy production processes and reducing resource waste. Additionally, the fractured behavior of rocks in geothermal systems is closely related to underground water flow and geological hazards, bearing importance for groundwater resource management and geological disaster prevention.

Multiscale fractured simulation research encompasses several aspects: ① cross-scale simulations from micro to macro scales to deeply understand the thermal, hydrological, and mechanical interactions within rocks in geothermal systems; ② coupling experimental research and numerical simulations to validate the accuracy of simulation results; ③ development of efficient algorithms and simulation tools to enhance computational efficiency of multiscale simulations; and ④ application of real-time monitoring and data acquisition techniques to improve the accuracy of simulation models.

In the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”, the main contributing countries are China, the USA, and Australia (Table 1.2.13 and Figure 1.2.10). The primary contributing institutions are Xi’an University of Technology, China University of Mining and Technology, Chengdu University of Technology, and Purdue University (Table 1.2.14). These four institutions have substantial collaboration (Figure 1.2.11). The top three countries in terms of citing papers are China, the USA, and Australia (Table 1.2.15). The main output institutions of citing core papers are China University of Mining and Technology, Xi’an University of and Technology, Henan Polytechnic University, Anhui University of Science and Technology, and Purdue University (Table 1.2.16).

The roadmap of the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems” is presented in Figure 1.2.12. The future development direction will center on following aspects. ① High-precision model construction, coupling effects study, and data-driven simulation. Future research on high-precision model construction will focus on more refined model construction, including inputting more accurate rock physical parameters, pore structures, and geological fracture characteristics. This will contribute to more realistic simulations of the complex thermal-hydro-mechanical coupling behaviors within geothermal systems. ② Coupled effects study will focus on the coupling effects between different scales and different physical processes, exploring the impact of rock thermal, hydrological, and mechanical interactions on geothermal system behaviors. ③ Data-driven simulation will integrate more actual monitoring data to validate model accuracy, optimize parameters, and enhance the reliability of simulation results.

The future development trend in “multiscale fractured modeling and simulation of coupled thermo-hydro mechanical processes in rocks for geothermal systems” will center on followings. ① Multi-physics field coupling: Beyond thermal-hydro mechanical coupling, future research will consider interactions between multiple physical fields such as chemistry and fluid flow, achieving more comprehensive geothermal system simulations. ② High-performance computing application: As computing capabilities improve, future simulation research will increasingly rely on high-performance computing to enable finer and more complex simulations for accurately predicting geothermal system behaviors.

Geothermal energy, as a sustainable form of clean energy, has tremendous potential. Multiscale simulation research contributes to a better understanding of geothermal resource distribution, variations, and sustainable utilization methods. This is crucial for improving development efficiency and reducing environmental risks associated with geothermal energy.

Multiscale fractured simulation research has broad applications in geothermal resource exploration, development, and

Table 1.2.13 Countries with the greatest output of core papers on “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	11	100.00	379	34.45	2021.5
2	USA	4	36.36	118	29.50	2021.2
3	Australia	1	9.09	65	65.00	2022.0

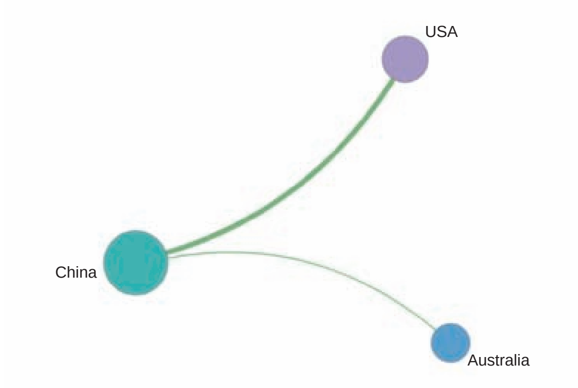

Figure 1.2.10 Collaboration network among major countries in the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

Table 1.2.14 Institutions with the greatest output of core papers on “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Xi’an University of Technology	8	72.73	348	43.50	2021.4
2	China University of Mining and Technology	5	45.45	221	44.20	2021.4
3	Chengdu University of Technology	4	36.36	156	39.00	2021.2
4	Purdue University	4	36.36	118	29.50	2021.2
5	Henan Polytechnic University	4	36.36	42	10.50	2021.5
6	Monash University	1	9.09	65	65.00	2022.0
7	Beijing Research Institute of Uranium Geology (ALBRIUG)	1	9.09	49	49.00	2021.0
8	Hohai University	1	9.09	49	49.00	2021.0
9	Xi’an University of Science and Technology	1	9.09	43	43.00	2021.0
10	Xuzhou University of Technology	1	9.09	23	23.00	2021.0

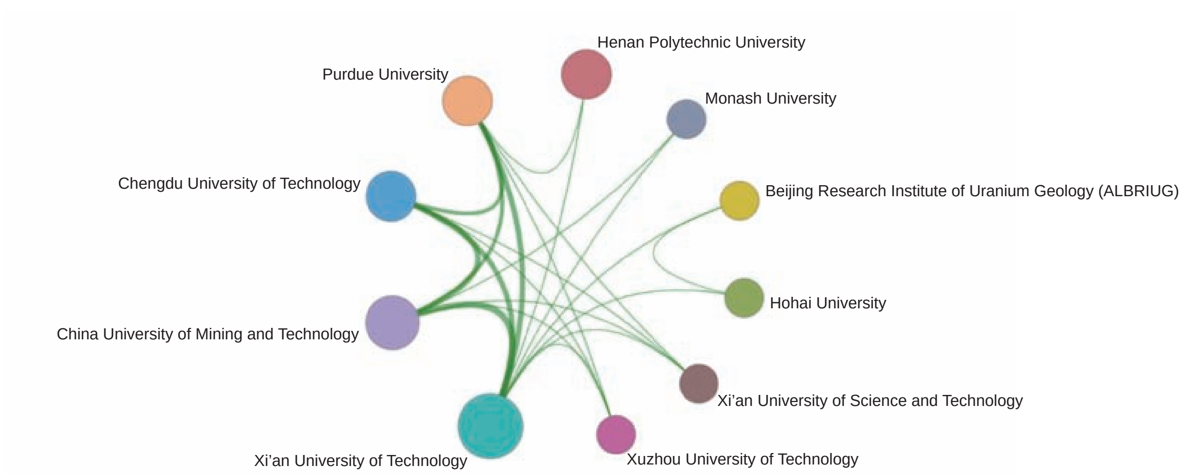

Figure 1.2.11 Collaboration network among major institutions in the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

Table 1.2.15 Countries with the greatest output of citing papers on “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	190	84.07	2021.9
2	USA	16	7.08	2021.8
3	Australia	8	3.54	2021.8
4	Poland	3	1.33	2022.0
5	UK	2	0.88	2022.0
6	Japan	2	0.88	2022.0
7	Iran	1	0.44	2021.0
8	Russia	1	0.44	2021.0
9	India	1	0.44	2021.0
10	Portugal	1	0.44	2022.0

Table 1.2.16 Institutions with the greatest output of citing papers on “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	China University of Mining and Technology	55	28.21	2021.8
2	Xi’an University of Technology	30	15.38	2021.8
3	Henan Polytechnic University	22	11.28	2021.7
4	Anhui University of Science and Technology	15	7.69	2021.9
5	Purdue University	14	7.18	2021.7
6	Xi’an University of Science and Technology	12	6.15	2021.9
7	Chongqing University	11	5.64	2021.9
8	Xuzhou University of Technology	11	5.64	2021.6
9	Shandong University of Science and Technology	11	5.64	2021.9
10	Guizhou University	8	4.10	2022.0

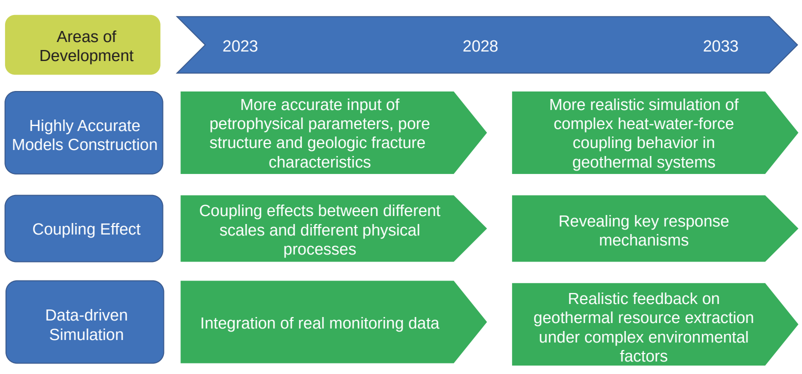

Figure 1.2.12 Roadmap of the engineering research front of “multiscale fractured modeling and simulation of coupled thermo-hydro-mechanical processes in rocks for geothermal systems”

management. In geothermal energy extraction processes, it can aid in predicting geothermal system behaviors, optimizing production plans, and reducing production risks. Furthermore, it can be applied to the study of interactions between geothermal energy, groundwater, and geological environments, as well as in designing integrated utilization schemes of geothermal energy and other energy forms.

2 Engineering development fronts

2.1 Trends in Top 12 engineering development fronts

The Top 12 engineering development fronts assessed by the Energy and Mining Engineering Group are shown in Table 2.1.1. These fronts involve the fields of energy and electrical science, technology, and engineering; nuclear science, technology, and engineering; geology resources science, technology, and engineering; and mining science, technology, and engineering. In these 12 engineering development fronts, “fast charging and management technology for batteries”, “long-term and large-scale thermal energy storage and thermo-mechanical energy storage technologies”, and “data-driven technology for security operation and monitoring system of intelligent power distribution networks” represent the engineering development front of energy and electrical science; “fast reactor metal fuels, nitride & carbide fuel and fuel cycles”, “deuterium tritium operation experiment of device Tokamak”, and “nuclear energy hydrogen production-industrial application coupling technology” represent the engineering development front of nuclear science, technology, and engineering; “exploration method for mineral deposits utilizing high-precision ground gravity measurement”, “seismic data interpretation and utilization based on deep learning”, and “research and development of portable geological exploration and sampling device” represent the engineering development front of geology resources science, technology, and engineering; “research on intelligent collaborative platform for oil and gas exploration and development”, “optimal and rapid drilling technology of long horizontal well on large platform in shale reservoir”, and “research and development of intelligent perception drilling detection equipment for coal mines under complex conditions” represent the engineering development front of mining science, technology, and engineering.

The disclosure of core patents involved in each development front from 2017 to 2022 is presented in Table 2.1.2.

(1) Fast charging and management technology for batteries

The capability of Li-ion/Na-ion batteries determines the competitiveness and performance of electric vehicles. The full charging time of the existing power battery is about 60 minutes, which is 20 times of the refueling time of the car. As a result, achieving fast-charging can enhance the market share and broaden applications of electric vehicles. The United States Advanced Battery Consortium has proposed specific indicators for power battery charging, requiring 80% of the total battery power to be charged within 15 min. However, due to the polarization from sluggish ion transport, fast-charging often causes metal plating at the anode side, leading to capacity decay and safety issues. Management technologies and battery material modification are two major strategies towards fast-charging. These strategies enhance the fast-charging capability of batteries by lowering the energy barrier of the rate-limiting step for the entire charging process. The aforementioned management technologies include battery intelligent temperature control system and algorithm optimized charging protocol, while material modification mainly focuses on electrode design, anode material, binder, electrolyte, and solid electrolyte interphase (SEI). Nevertheless, rate-limiting step of the entire charging process is hard to identify, and may varies with external conditions or cycling parameters, which makes strategies aiming at a single step less effective. Under this circumstance, it is necessary to switch from suppressing Li or Na plating to regulating Li or Na plating. Through a series of metal plating regulation methods such as SEI engineering, a uniformly-distributed, less-dendritic, and highly-reversible Li or Na plating at the anode side in fast-charging operations can be realized. This not only intrinsically solves safety problems from Li or Na dendrite plating, restoring the cycling life, but also increases the state of charge under fast-charging. Therefore, this Li or Na plating regulation as well as morphology control is one of the most important tendencies in future development of fast-charging, which is an important trend in the development of fast charging technology in the future.

Table 2.1.1 Top12 engineering development fronts in energy and mining engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Fast charging and management technology for batteries	464	15 925	34.32	2018.5
2	Fast reactor metal fuels, nitride & carbide fuel and fuel cycles	312	507	1.62	2019.9
3	Exploration method for mineral deposits utilizing high-precision ground gravity measurement	342	5 472	16.00	2018.5
4	Research on intelligent collaborative platform for oil and gas exploration and development	275	618	2.25	2020.4
5	Long-term and large-scale thermal energy storage and thermo-mechanical energy storage technologies	1 616	2 558	1.58	2020.1
6	Data-driven technology for security operation and monitoring system of intelligent power distribution networks	109	3 137	28.78	2019.0
7	Deuterium tritium operation experiment of device Tokamak	143	216	1.51	2020.0
8	Nuclear energy hydrogen production-industrial application coupling technology	142	181	1.27	2019.8
9	Seismic data interpretation and utilization based on deep learning	336	4 714	14.03	2019.1
10	Research and development of portable geological exploration and sampling device	872	497	0.57	2020.3
11	Optimal and rapid drilling technology of long horizontal well on large platform in shale reservoir	392	8 076	20.60	2018.6
12	Research and development of intelligent perception drilling detection equipment for coal mines under complex conditions	178	1 930	10.84	2019.8

Table 2.1.2 Annual number of core patents published for the Top 12 engineering development fronts in energy and mining engineering

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Fast charging and management technology for batteries	136	119	96	73	39	1
2	Fast reactor metal fuels, nitride & carbide fuel and fuel cycles	43	32	54	49	65	69
3	Exploration method for mineral deposits utilizing high-precision ground gravity measurement	92	94	70	56	26	4
4	Research on intelligent collaborative platform for oil and gas exploration and development	9	31	40	36	71	88
5	Long-term and large-scale thermal energy storage and thermo-mechanical energy storage technologies	178	210	219	225	319	465
6	Data-driven technology for security operation and monitoring system of intelligent power distribution networks	22	21	24	21	18	3
7	Deuterium tritium operation experiment of device Tokamak	14	18	25	21	27	38
8	Nuclear energy hydrogen production-industrial application coupling technology	24	21	17	15	26	39
9	Seismic data interpretation and utilization based on deep learning	51	68	86	70	56	5
10	Research and development of portable geological exploration and sampling device	51	101	82	176	237	225
11	Optimal and rapid drilling technology of long horizontal well on large platform in shale reservoir	104	84	103	52	47	2
12	Research and development of intelligent perception drilling detection equipment for coal mines under complex conditions	18	15	22	58	64	1

(2) Fast reactor metal fuels, nitride & carbide fuel and fuel cycles

There are two types of fast reactor fuel that have been used internationally, ceramic fuel and metal fuel. Fast reactor metal fuel, nitride and carbide fuel are being developed internationally. Such fuels have a higher breeding ratio than oxide fuels.

Metal fuel has the characteristics of high thermal conductivity, low fuel temperature, and high safety margin. The swelling can be inhibited by the improvement of material technology. Fast reactor metal fuel is recognized as one of the main types of fast reactor fuel in the future. The metal fuel manufacturing process is more simplified, and the metal fuel and dry reprocessing (separated metals are U and Pu) can better directly cooperate with the production of new fuels, forming an integrated fuel cycle system.

The research and development of metal fuel mainly focuses on U-Zr alloy and U-Pu-Zr alloy. The metal fuel usually consists of a binary alloy of U-10Zr alloys or a ternary alloy of U-Pu-10Zr. MAs is added to oxide fuel and metal fuel to become transmutation fuel.

Mixed plutonium-uranium nitride fuel and carbide fuel are new fuel forms under development. The plutonium uranium density of UPuN and UPuC is higher than that of oxide fuel, which can obtain a higher breeding ratio, a shorter breeding time, a better thermal conductivity, and an excellent compatibility with sodium coolant and stainless-steel cladding.

Many countries in the world have conducted the research and development and application of carbide and carbide fuel. The USA, France, Russia, India, and other countries have conducted research and development of a variety of carbides and carbide fuels. Russian Fast Reactor (in addition to MOX) fuel selected mixed nitride fuel (MNUP) as one of the future fast reactor fuel options. The experimental fast reactor FBTR in India uses carbide (Pu, U)C fuel.

(3) Exploration method for mineral deposits utilizing high-precision ground gravity measurement

Ground gravity measurement refers to the method of utilizing the gravimeter to measure the gravity at a certain point on the ground, and utilizing the change of underground density reflected by the gravity for mineral exploration. It is one of the important geophysical prospecting methods to conduct regional geological research, mineral exploration and resource investigation by analyzing the characteristics of relative gravity and absolute gravity.

The technology of ground gravity measurement has been greatly developed in China and abroad. Based on the idea of zero-length spring, the USA and Canada have designed and produced a quartz spring gravimeter which has a measurement accuracy of 5 μGal. China has reached 30 μGal. A quartz spring gravimeter has played a significant role in mineral exploration, and is still the main technical equipment in the world. However, the traditional spring gravimeter has been developed to the extreme level, with little margin for improving measurement accuracy.

At present, based on the principle of atomic interference, a number of ground absolute gravimeters and gravity gradiometers have been developed in China and abroad. The absolute gravimeter measurement sensitivity reaches 4.2–44.0 μGal/$Hz^{1/2}$, the gravity gradiometer can measure the gravity gradient signal to 170 E, and the probe volume is significantly reduced. As a new generation of quantum gravity sensor, the atomic gravimeter is expected to have a measurement sensitivity of 10^{-4} μGal. However, it faces with challenges such as miniaturization and improved measurement accuracy. Atomic gravimeter also faces problems such as insufficient scaling factor and low phase extraction efficiency. The atomic gravimeter also faces enormous challenges in practical application.

The main research direction is the development of miniaturized and high-precision atomic absolute gravimeter/gravity gradiometer, fine data processing and interpretation, etc., providing more accurate and technologically more advantageous exploration technologies, which has important practical and strategic significance for building the security of China's mineral resources.

(4) Research on intelligent collaborative platform for oil and gas exploration and development

The intelligent collaborative platform for oil and gas exploration and development refers to the provision of an integrated environment that encompasses information sharing, technological innovation, production and operation integration, and intelligent collaboration, facilitating multidisciplinary interaction and integrated exploration and development. In the current wave of oil and gas technological and digital revolutions, the integration of new technologies such as big data and artificial intelligence with the oil and gas industry has become a significant avenue for innovation. Foreign oil and gas companies, such as Shell, Schlumberger, Halliburton, BP, Chevron, and Eni, have made initial progress in constructing intelligent platform solutions for exploration and development. However, the global informatization level of the oil and gas industry remains relatively low, far below the industry average. Presently, China is still in the transitional phase from digitization to intelligence. China National Petroleum Corporation (CNPC) has made phased progress in establishing the "Exploration and Development Dream Cloud" platform. Sinopec has built the "Petrochemical Intelligence Cloud" platform, and China National Offshore Oil Corporation (CNOOC) has constructed collaborative working environments and systems for onshore and offshore exploration and development. Yet, the overall development still lags behind international counterparts.

The key research directions include artificial intelligence technology, intelligent oil and gas exploration, integrated geological engineering, intelligent equipment research and development, cloud computing platform construction, and data sharing, etc. The developmental trend involves the organic integration of hardware facilities, software development, digital technology, and oil and gas expertise, culminating in a fully digitized, automated, and intelligent professional application environment for exploration and development. It is expected to change the mode of exploration and development work, enhance efficiency, maximize comprehensive benefits, propel the digital transformation and intelligent development of the oil and gas industry, and safeguard national energy security.

(5) Long-term and large-scale thermal energy storage and thermo-mechanical energy storage technologies

Thermal energy storage (TES) and thermo-mechanical energy storage (TMES) technologies are energy storage techniques based on heat and mass transfer, and reversible heat-work conversion. They make large-scale energy storage possible from both technical and economic perspectives and realize long-term and seasonal energy storage. With advantages such as high energy density, flexible utilization, high overall efficiency and controllable costs, they are crucial for promoting the green transformation of energy and building zero-carbon power systems based on renewable energy sources. TES technologies include sensible heat storage, latent heat storage, and thermochemical heat storage. TMES technologies encompass compressed-air/CO_2 energy storage, liquid-air/CO_2 energy storage, and Carnot battery (also known as pumped-thermal electricity/energy storage).

The main technical directions for long-term and large-scale TES and TME technologies include the construction of multiscale coupling mechanisms between heat storage and heat/mass transfer, active control strategies for the physical and chemical properties of heat storage materials, the development and preparation of safe and effecient encapsulation and insulation materials, structural optimization techniques for heat storage units based on the topology optimization theory and AI algorithms, high entropy efficiency compression and expansion techniques under extreme temperature and pressure conditions, thermodynamic and economic analyses of TES and TMES systems, and intelligent operation and control techniques for multi-scenario operation of TES and TMES systems.

The development trend in this field at the material level is that novel composite heat storage materials can be designed and prepared actively based on comprehensive considerations of their thermo-physical properties, corrosiveness, and stability. At the component level, combined with additive manufacturing technologies such as 3D printing, heat storage units and compressors/turbines with a high degree of freedom for specific targets can be explored and developed. At the system level, TES and TMES systems can be integrated with the zero-carbon power and fuel systems, and extend to smart energy systems that provide flexible energy solutions.

(6) Data-driven technology for security operation and monitoring system of intelligent power distribution networks

As informatization and automation of intelligent power distribution networks continues to improve, the amount of data collected from the operation of power distribution networks has increased dramatically. At the same time, the deep integration of power distribution networks and the Internet of Things has also promoted data interaction within and outside power companies. There gradually forms a big data environment for the secure operation and monitoring of intelligent power distribution networks. However, the types of data obtained from power distribution networks are diverse and the granularity of data is high. In addition, the correlation between online and offline data is extremely complex. Existing model-based analysis, calculation, and optimization control methods for power distribution networks cannot be adapted for practical application. It is urgent to explore data-driven analysis and decision-making, operation optimization, monitoring and control technologies for intelligent power distribution networks to achieve comprehensive intelligent improvement in monitoring, dispatching, protection, control of power distribution systems empowered by big data. The main research directions of data-driven secure operation and monitoring technology for intelligent power distribution networks include development of multi-parameter sensors and edge computing devices for intelligent power distribution networks; security and privacy protection mechanisms for distribution network data communication networks; operation situation awareness and digital twin AI modeling technology for intelligent power distribution networks; multiscale, refined data mining and data fusion technology for intelligent power distribution networks; data-driven aggregation control and interactive support technology for massive demand-side resources in power distribution systems; data-driven source-network-load-storage optimization scheduling method for intelligent power distribution networks; and protection and control technology for smart distribution networks based on fault data mining.

(7) Deuterium tritium operation experiment of device Tokamak

Magnetic confinement deuterium-tritium fusion based on tokamak is by far the most promising way for the development of controlled fusion energy. In the context of “carbon neutrality” and the increasing demand for energy in the long-term development, developing fusion energy is the ultimate way to solve energy problems. Tritium is a rare radioactive isotope that, when fused with the isotope deuterium, produces more neutrons and energy output compared to reactions between deuterium-deuterium particles. Deuterium-tritium reaction reaches fusion conditions at lower temperatures compared to other elements. However, due to the short half-life of tritium and difficulties in preparation, its price is extremely high. Only deuterium is used in most of the experiment in devices at present. Therefore, in order to verify the physical and engineering challenges involved in deuterium-tritium fusion reactions, the International Thermonuclear Experimental Reactor (ITER) is scheduled to conduct deuterium-tritium plasma experiments starting from 2035. By conducting deuterium-tritium fusion experiments, fusion performance can be directly verified, tritium related behavior in tokamak can be analyzed, and deuterium-tritium plasma behavior, alpha particle behavior, and their impact on plasma can be studied. The key issues in tokamak deuterium- tritium experiments include alpha particle heating related physics, plasma energy confinement, isotope effect, particle transport, magnetohydrodynamic (MHD) stability, fusion power production, demonstration of safe handling of tritium, tritium breeding system, safe remote maintenance of tokamak, etc.

(8) Nuclear energy hydrogen production-industrial application coupling technology

Compared with traditional hydrogen production technologies, nuclear energy hydrogen production has advantages such as cleanliness, high efficiency, and economy. Therefore, the scientific research and industrial application of nuclear energy hydrogen production have gradually become a hot spot. Electrolytic water hydrogen production —the direct application of hydrogen or the form of energy storage for power generation is expected to become another commercial application of large-capacity long-term energy storage technology besides pumped storage. At the same time, the industrial application of nuclear energy hydrogen production includes the supply of diversified products of water, electricity, and hydrogen from nuclear energy to petrochemical parks, to supply water thermoelectric hydrogen diversified products, and the application in the fields such as fuel synthesis and metallurgy.

Applications in hydrogen and synthetic fuel production include the production of hydrogen by Cu-Cl thermochemical mixing cycle utilizing the heavy water reactor ACR-700 in Canada. Germany has utilized the prototype reactor to produce process heat and produce mixed gas through coal gasification. Japan has proposed the concept of utilizing GTHTR300C for hydrogen production. South Africa has proposed the concept of PBMR with steam improvement and thermochemical sulfur mixing cycle. The USA has proposed a plan for hydrogen production by high-temperature steam electrolysis utilizing H_2-MHR. Japan proposed the concept of utilizing GTHTR300C to make steel. There are also hydrogen-based green fuel synthesis technology, the hydrogen metallurgy technology, the coal ammonia mixed combustion technology, and the hydrogen doped/hydrogen burning turbine technology. The coupling technology of hydrogen energy industrial applications mainly include process simulation and optimization, high-efficiency reactor, corrosion resistance test of engineering materials, measurement and control technology of engineering materials.

(9) Seismic data interpretation and utilization based on deep learning

The fields of Earth science and energy are undergoing unprecedented changes by deep learning. The seismic interpretation technology based on deep learning simulates the neural structure of the human brain to achieve automatic learning and analysis of seismic data, which brings great potential for geological exploration, reservoir prediction and oil and gas development. Foreign companies such as Schlumberger, CGG, and Halliburton have made significant progress in the seismic interpretation technology based on deep learning. They have successively launched intelligent fault identification, layer pickup, and seismic analysis, and other products, achieving efficient and accurate structural interpretation and reservoir analysis function, providing important technical support for energy exploration and development. At present, China is faced with challenges such as deep ultra-deep exploration, unconventional heterogeneous reservoir, engineering dessert prediction, and improving oil recovery in abandoned oil and gas fields. New and higher requirements are proposed for high-precision seismic interpretation technology. The seismic data interpretation technology based on deep learning is expected to become the key to improving the efficiency of oil exploration and oil and gas development. China has made phased progress. Although individual technologies have ranked in the forefront of the world, the overall level still needs to be improved. The research direction of the seismic interpretation technology based on deep learning includes the intelligent logging analysis technology, intelligent structure interpretation, reservoir prediction and reservoir development, etc. The future development will cover multi-physical field data fusion, the construction of an automated interpretation platform, intelligent description of reservoirs, and real-time seismic monitoring. The integration of seismic data with other geological and geophysical data will further improve the accuracy and reliability of interpretation. At the same time, an intelligent interpretation platform should be established to realize the integrated process from data pre-processing to result visualization. In addition, deep learning techniques will be combined with geological simulation to achieve intelligent description of reservoir properties to assist in oil reservoir evaluation and optimization. These technologies will bring new breakthroughs to geoscience and energy.

(10) Research and development of portable geological exploration and sampling device

The portable geological exploration and sampling device consists of portable drilling rig, sampling tools, flushing fluid circulation system and other apparatus. It is based on a lightweight and modular design, easy to disassemble and transport, and suitable for geological exploration sampling in areas with inconvenient transportation and limited construction sites. A relatively complete technology and equipment system has been established abroad. The equipment in China has similar drilling capabilities to foreign countries, However, there are still gaps in sampling technology system construction, and equipment automation, and other aspects. At present, the key investigation areas for the new round of strategic breakthrough in mineral exploration in China have shifted to areas like coverage areas, mid to high mountains, and deep cutting areas. Portable geological exploration and sampling devices are key technical equipment for coordinating mineral exploration and development, ecological protection, and practicing green exploration. The main research directions for the development of portable geological exploration and sampling devices include light weighting of drilling rigs, high-efficiency drilling process, electrification and automation upgrading, and integration of comprehensive technology for green exploration. The development trend of portable geological exploration and sampling devices include the optimization of structure, materials, and automation upgrade of drilling process, to improve the portability of drilling rigs and reducing personnel labor intensity; realization of green exploration through the research and application of technologies such as clean energy driven, environmentally friendly flushing fluids, and mud non-landing system; the study of sampling technology system, which meets the requirements of different geological conditions and geological needs for efficient in-situ pollution-free sampling; the integration of multiple processes and carriers of one drilling rig, to achieve multiple functions and improve problem-solving capabilities; and the research of supporting parameter monitoring system, in combination with the artificial intelligence technology, to achieve diagnosis of working conditions, lithology identification and so on.

(11) Optimal and rapid drilling technology of long horizontal well on large platforms in shale reservoir

Shale reservoirs have the characteristics of "low porosity and low permeability", whose production relies on horizontal drilling and hydraulic fracturing technologies. The optimal and rapid drilling technology of long horizontal well on large platform refers to the simultaneous arrangement of multiple long horizontal wells on a single platform to reduce the occupied area of the well site, increase the control volume of the underground oil and gas reservoir, achieve high-quality and rapid drilling in shale reservoirs, shorten drilling cycles, and lower operational costs. The USA and Canada were pioneers in commercial shale oil and gas production, while China is accelerating its entry into the phase of industrialized commercial production. The Southwest oil and gas field drilled China's first shale gas horizontal well and the first commercially valuable shale gas well. Changqing Oilfield has established the largest onshore shale oil long horizontal well platform in Asia, the Hua H100 platform. The horizontal section of well H90-3 measures 5 060 meters, marking the longest onshore horizontal section length in Asia. However, compared to the primarily marine shale reservoir conditions in North America, the predominantly terrestrial shale reservoirs in China are buried deeper, have complex topography, poor stratigraphic continuity, intense fragmentation, high technical requirements and development costs, posing significant drilling and production challenges. The main research directions include factory-like operation techniques, optimized horizontal well trajectory, accelerated horizontal well supporting technologies, wellbore structure optimization, enhanced drilling parameters, drilling fluid system optimization, speed-enhancing equipment development, efficient directional drilling patterns, and comprehensive friction reduction and sliding guidance technology research. Undertaking large-scale operations based on long horizontal wells as a foundation, researching efficient drilling and completion techniques, holds the potential to facilitate the efficient development of shale oil and gas in China.

(12) Research and development of intelligent perception drilling detection equipment for coal mines under complex conditions

Research and development of intelligent perception drilling detection equipment for coal mines under complex conditions is an advanced technological apparatus designed to address the complex conditions and high risks of deep coal mining environments. Its core concept involves integrating artificial intelligence, the sensor technology, data analysis, and related fields to make the drilling process more intelligent, automated, and capable of perceiving real-time underground mining conditions in real-time, ensuring the safety of miners and enhancing the efficiency of mining.

In terms of primary technological directions, the development of intelligent perceptive drilling equipment for coal mines covers several key areas. The first is the development of high-precision sensor technology, including geological exploration sensors, temperature-humidity sensors, gas detection sensors, etc. which can monitor the physical parameters and environmental conditions of underground coal seams in real time. The second is the development of data collection and processing technology which is the foundation for intelligent perception. By utilizing big data analysis and machine learning algorithms, data collected by sensors is transformed into useful information, predicting potential risks and making corresponding decisions. The last is the development of the automation control technology, the utilization of which can automate the drilling processes, reduce manual intervention, thereby minimizing accident risks.

With ongoing technological advancements, the development trends of intelligent perceptive drilling equipment for coal mines are becoming increasingly apparent. On the one hand, more emphasis will be placed on multi-modal data fusion, incorporating data from various types of sensors to achieve comprehensive underground information gathering. On the other hand, more emphasis will be placed on intelligent decision-making support, utilizing advanced algorithms and models to achieve automated risk prediction and emergency response. Additionally, breakthroughs in communication technology are anticipated, enabling real-time data transmission between the underground environment and surface command centers, thereby enhancing the efficiency of overall emergency response.

2.2 Interpretations for four key engineering development fronts

2.2.1 Fast charging and management technology for batteries

Realizing fast charging of batteries can enhance the market share and broaden the application of electric vehicles. When charging a battery, Li or Na ions leave from layered cathodes and get solvated with electrolyte solvents, all the way heading for the anode side through electrolyte and are finally inserted into layered anodes. The precise understanding of the rate-limiting step of the above charging process remains controversial, but it is widely believed that ion de-solvation, transport in SEI, and diffusion in anode are possible rate-limiting steps. The inferior kinetics of the rate-limiting step increase the internal resistance of the battery during fast-charging, thus causing Li or Na plating on anode surface, which eventually leads to safety problems and capacity decay.

The battery management technology and material modification can effectively enhance the fast-charging performance. The management technology includes battery intelligent temperature control system and algorithm optimized charging protocol. The former can heat the cell to an elevated temperature to boost the ion conduction, thus reducing the resistance of the rate-limiting step. However, the control of the temperature with surgical precision is challenging. The latter can balance and optimize multiple signals and parameters inside a cell, though there is still lack of data supporting.

Battery material modification include the research in electrode design, anode material, binder, electrolyte and SEI. Electrode with three-dimensional and gradient design can enhance active reacting interfaces, thereby accelerating ion diffusion. However, due to cost, fabrication, and energy density limitations, this solution is currently difficult to popularize. Advanced anode materials such as silicon, red/black phosphorus have excellent fast-charging capabilities. However, their electrical conductivity and volume expansion still need extensive research efforts. Mixed ion-electron conducting binders are also designed for fast-charging applications. However, it is difficult for mass production. Electrolyte with weak solvation structure can be used in fast-charging operations, but the difficulty is how to improve the oxidative stability and voltage window of such electrolytes. SEI engineering, by constructing a inorganic-rich SEI, has been confirmed to be effective in enhancing fast-charging capability. In addition, this strategy can also regulate Li or Na plating and tuning its morphology, ensuring a uniform, dendrite-free, and high-reversible plating behavior, which not only can solve the intrinsic problems caused by dendrites plating, but also can achieve a 100% state of charge for fast-charging.

In the engineering research front of “fast charging and management technology for batteries”, China ranks first in the world with 217 published patents, accounting for 46.77%, followed by the USA, Japan, and Republic of Korea (Table 2.2.1). Of all the parties, the USA and Republic of Korea have extensive cooperation, while China has cooperation with the USA and Canada (Figure 2.2.1). Institutions with large number of published patents are Nanotek Instruments Incorporated, Samsung Electronics Company Limited, Tsinghua University, and Ningde Contemporary Amperex Technology Limited (Table 2.2.2). Nanotek Instruments Incorporated has very close cooperation with Global Graphene Group Incorporated. United Technologies Corporation has extensive cooperation with Raytheon Corporation. Tsinghua University and Ningde Contemporary Amperex Technology Limited have close cooperation (Figure 2.2.2).

Realizing fast-charging procedure for Li-ion and Na-ion batteries depends on the synergistic development of battery material modification and management technology. For battery management technology, it is necessary to further develop the temperature control system and charge protocol, in order to achieve precise tuning of cell temperature, reduced system volume and cost. It is also important to complete algorithm network and realize real-time feedback for battery status. A more effective charge protocol with large output power and accurate monitoring of Li or Na plating at anode side is also highly desired. In the area of battery material modification, it is essential to design three-dimensional electrode, functional binder, weak-solvation electrolyte, and inorganic component-based SEI that significantly reduces internal resistance and inhibits Li or Na plating. In addition, the anode material should be switched gradually from carbon-based to silicon-based and eventually phosphorus-based materials. Moreover, based on the previous research, SEI engineering is still needed to regulate Li or Na plating during fast-charging operations, towards a uniformly-distributed, non-dendritic and highly-reversible Li or Na plating at anode side. Finally, this advanced battery with multiple technologies integrated is expected to realize a 3-minute fast- and full-charging performance on electric vehicles. The roadmap of the engineering development front of “fast charging and management technology for batteries” is presented as Figure 2.2.3.

Table 2.2.1 Countries with the greatest output of core patents on "fast charging and management technology for batteries"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	217	46.77	5 840	36.67	26.91
2	USA	144	31.03	6 002	37.69	41.68
3	Japan	37	7.97	1 481	9.30	40.03
4	Republic of Korea	34	7.33	1 448	9.09	42.59
5	Canada	9	1.94	329	2.07	36.56
6	Germany	9	1.94	321	2.02	35.67
7	UK	6	1.29	194	1.22	32.33
8	Israel	5	1.08	270	1.70	54.00
9	Denmark	4	0.86	118	0.74	29.50
10	France	2	0.43	61	0.38	30.50

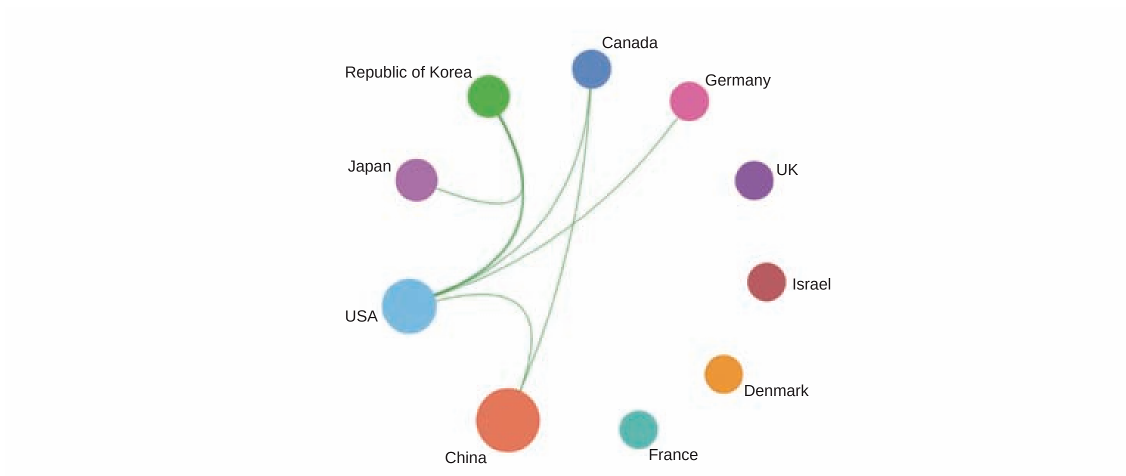

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "fast charging and management technology for batteries"

Table 2.2.2 Institutions with the greatest output of core patents on "fast charging and management technology for batteries"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Nanotek Instruments Incorporated	37	7.97	1 738	10.91	46.97
2	Samsung Electronics Company Limited	21	4.53	912	5.73	43.43
3	Global Graphene Group Incorporated	19	4.09	850	5.34	44.74
4	United Technologies Corporation	19	4.09	658	4.13	34.63
5	General Electric Company	18	3.88	693	4.35	38.50
6	LG Chemistry Limited	10	2.16	425	2.67	42.50
7	Tsinghua University	10	2.16	356	2.24	35.60
8	Kabushiki Kaisha Toshiba	8	1.72	361	2.27	45.12
9	Ningde Contemporary Amperex Technology Limited	8	1.72	235	1.48	29.38
10	Raytheon Corporation	8	1.72	227	1.43	28.38

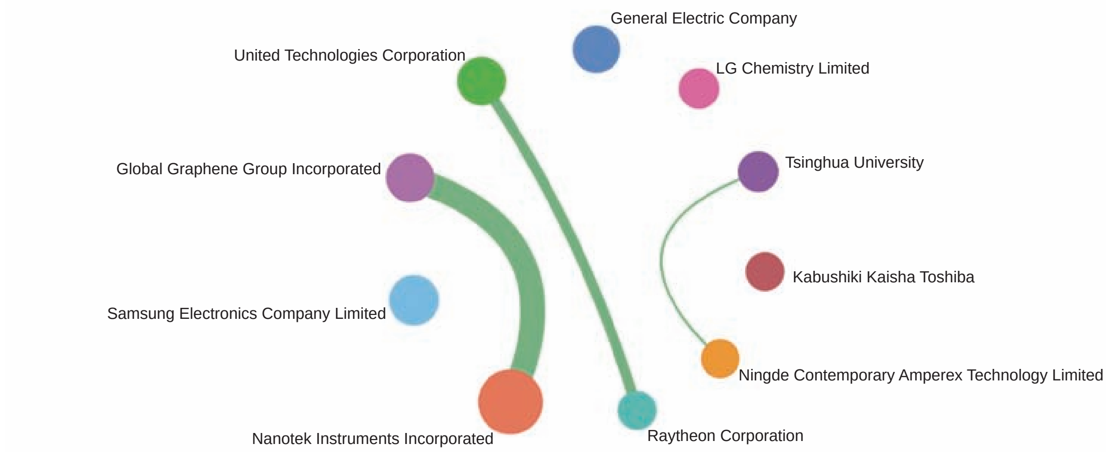

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of "fast charging and management technology for batteries"

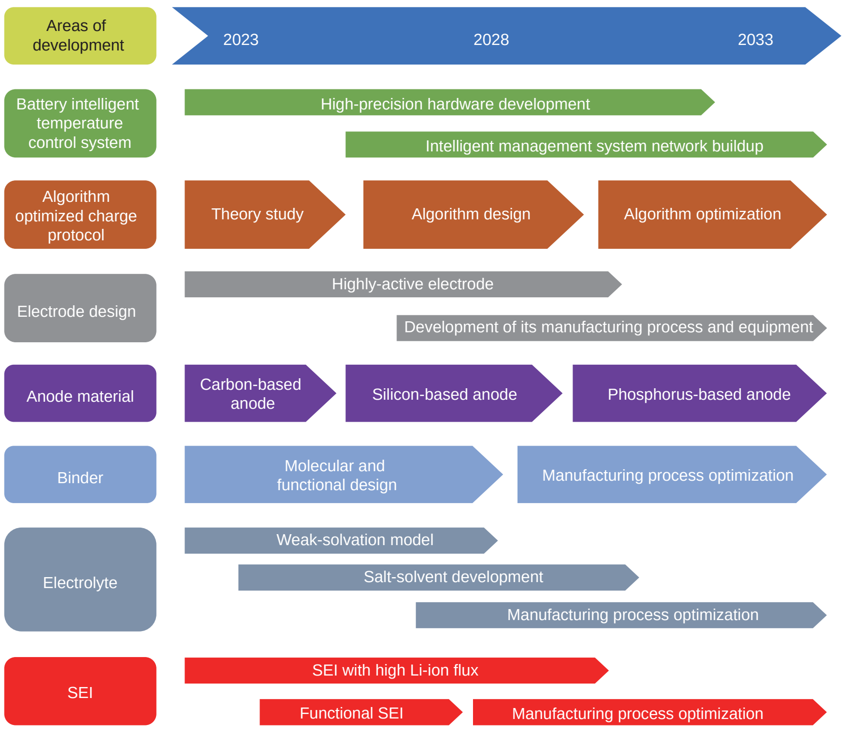

Figure 2.2.3 Roadmap of the engineering development front of "fast charging and management technology for batteries"

2.2.2 Fast reactor metal fuels, nitride & carbide fuel and fuel cycles

The fast reactor nuclear energy system can realize closed nuclear fuel cycle through nuclear fuel reprocessing, ensuring the sustainable development of nuclear energy. Utilizing fast reactor technology can effectively utilize ^{238}U (accounting for 99.3% of natural uranium), which can meet the needs of nuclear energy development based on domestic uranium resources. It can effectively incinerate long-life radioactive waste and solve the problem of environmental friendliness. High temperature and radiation resistance are the most important characteristics of fast reactor fuels, which means that the extended reactor life reduces the requirements for the outer part of the fuel cycle. Generating high power while maintaining a relatively low fuel temperature is also an important feature. Fast reactors can achieve fuel proliferation and MA transmutation, and recycle all elements, including uranium, plutonium and MA, through simplified and efficient dry reprocessing.

The nuclear fuel suitable for fast reactors should have a long in-reactor residence time, be able to withstand repeated power transients, be able to provide high power density, have a large margin to cope with overpower, good ability to cope with cladding failure, simple manufacturing, simple and economical post-processing technology and other characteristics. The advantages of metal fuel are good nuclear characteristics, hard energy spectrum, and close to the theoretical upper limit of proliferation. Nitride and fluoride nuclear fuels, still classified as ceramic fuels, have the advantage of a better proliferation capacity and a shorter fast reactor doubling time compared to oxide fuels. Another advantage of metallic fuel in sodium-cooled fast reactors is that the reactor can continue to operate without contaminating the coolant in the event of damage to the cladding and exposed fuel. In addition, the metal fuel greatly reduces the requirements of the fuel cycle outside the reactor. The manufacture is simple, easy, and cost-effective, with fewer post-treatment processes, and compact and economical recycling facilities. Deep burnup reduces the flow of fissile materials, thus, metallic fuels lay the foundation for a more economical fuel cycle.

Argonne National Laboratory in the USA developed the integrated fast reactor based on metal fuel from 1984 to 1994. TerraPower in the USA proposed the concept of traveling wave reactor around 2006 and conducted engineering design research. The traveling wave reactor has the characteristics of deep burnup, which can realize in-situ proliferation and incineration of ^{238}U in the reactor, so as to effectively improve the utilization rate of natural uranium resources through one pass. In 2012, Russia's national strategic plan for the peaceful use of nuclear energy "Breakthrough" program was officially launched, planning to build a fast reactor, closed fuel cycle technology, reprocessing, advanced nuclear fuel and new structural materials and other fields of engineering construction and related scientific research, to achieve the same site closed nuclear fuel cycle.

In terms of fast reactor technology, China has built a 65 MWt China Experimental Fast Reactor (CEFR) and is building a 600 MWe Demonstration Fast Reactor. Research on integrated fast reactor system is being conducted, which consists of a reactor and supporting fuel regeneration facilities. The reactor adopts a metal fuel fast reactor, and simultaneously realizes three functions of power generation, proliferation, and transmutation. The fuel regeneration facility integrates dry reprocessing and fuel manufacturing processes. The reactor and fuel recycling facilities are designed at the same site to realize the integration of closed fuel cycle processes.

Table 2.2.3 lists the main countries with the greatest output of core patents on "fast reactor metal fuels, nitride & carbide fuel and fuel cycles". It can be observed that the main output countries are China, Japan, and the USA, among which the amount of patent disclosure and the proportion of patent citations in China is much higher than that in other countries. There is no cooperation among major producing countries. As can be seen from Table 2.2.4, Nuclear Power Institute of China has disclosed a large number of patents. In terms of cooperation among major institutions, TerraPower Limited Liability Company has cooperated with General Electric Company, Nuclear Power Institute of China, and China Nuclear Power Technology Research Institute (Figure 2.2.4).

The roadmap of the engineering development front of "fast reactor metal fuels, nitride & carbide fuel and fuel cycles" is shown in Figure 2.2.5. The development goal of metal fuel is to master the manufacturing technology and process of U-Zr alloy, and it is expected to complete the irradiation test of U-Zr alloy metal fuel assemblies by 2030, with a burnup consumption of 150 GWd/tHM. The development path for the fast reactor and other advanced reactor fuels is to conduct research and development of nitride, carbide, U-Pu-Zr, U-Pu-Am-Zr alloy and other advanced fuels, and break through the manufacturing process and key technologies by 2033 to provide higher-performance fuel for advanced reactor.

Table 2.2.3 Countries with the greatest output of core patents on "fast reactor metal fuels, nitride & carbide fuel and fuel cycles"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	162	51.92	237	46.75	1.46
2	Japan	47	15.06	28	5.52	0.60
3	USA	39	12.50	196	38.66	5.03
4	Republic of Korea	26	8.33	10	1.97	0.38
5	Russia	23	7.37	9	1.78	0.39
6	Sweden	4	1.28	16	3.16	4.00
7	France	3	0.96	4	0.79	1.33
8	Canada	1	0.32	3	0.59	3.00
9	Italy	1	0.32	2	0.39	2.00
10	Germany	1	0.32	1	0.20	1.00

Table 2.2.4 Institutions with the greatest output of core patents on "fast reactor metal fuels, nitride & carbide fuel and fuel cycles"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Nuclear Power Institute of China	68	21.79	36	7.10	0.53
2	China Nuclear Power Technology Research Institute	19	6.09	30	5.92	1.58
3	General Electric Company	18	5.77	13	2.56	0.72
4	Korea Atomic Energy Research Institute	18	5.77	7	1.38	0.39
5	Mitsubishi Heavy Industries Limited	18	5.77	6	1.18	0.33
6	Xi'an Jiaotong University	17	5.45	49	9.66	2.88
7	TerraPower Limited Liability Company	16	5.13	119	23.47	7.44
8	Westinghouse Electric Company	14	4.49	42	8.28	3.00
9	Shanghai Institute of Applied Physics, Chinese Academy of Sciences	8	2.56	16	3.16	2.00
10	Kabushiki Kaisha Toshiba	8	2.56	5	0.99	0.62

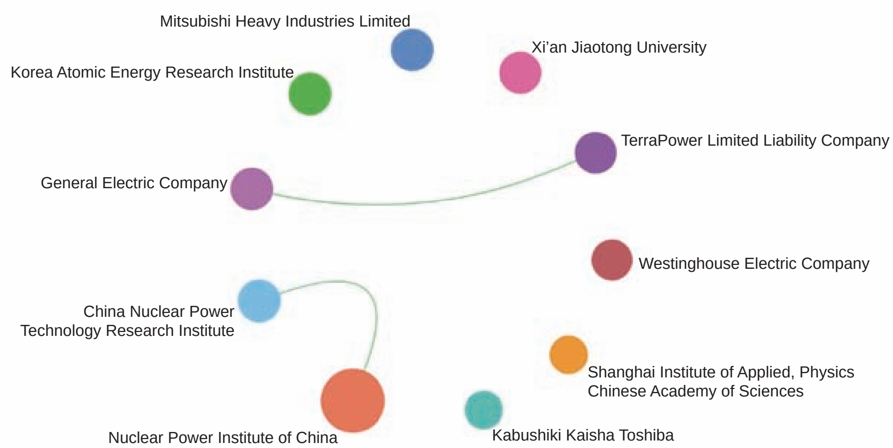

Figure 2.2.4 Collaboration network among major institutions in the engineering development front of "fast reactor metal fuels, nitride & carbide fuel and fuel cycles"

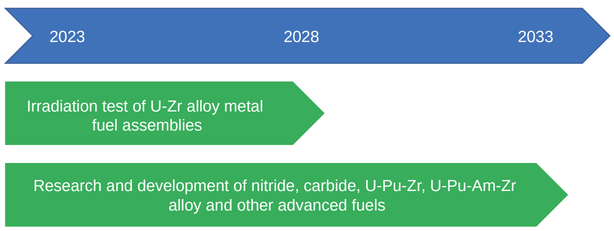

Figure 2.2.5 Roadmap of the engineering development front of “fast reactor metal fuels, nitride & carbide fuel and fuel cycles”

2.2.3 Exploration method for mineral deposits utilizing high-precision ground gravity measurement

The technology of ground gravity measurement has been greatly developed in China and abroad. Based on the idea of zero-length spring, a quartz spring gravimeter has been designed and produced by LaCoste Romberg in the USA and Scientrex in Canada. Scientrex has developed to the 6th generation CG-6 gravimeter, with a measurement accuracy better than 5 μGal, which has played a major role in mineral prospecting and is still the main technical equipment in countries around the world. The first gravimeter based on the cold atom interference principle was proposed by Stanford University in the 1990s, and the recent measurement sensitivity of the gravimeter based on this principle has reached 8 μGal/Hz$^{1/2}$. The University of Birmingham in the UK developed an atomic gravity gradiometer, which observed the gravity gradient signal of 170 E. A French company, iXblue, has developed the first mobile atomic gravity gradiometer in the world with an accuracy of less than 1 E, with a measuring resolution of 0.15 E.

China has also made progress, but the overall technology still lags behind foreign countries. In the 1990s, Beijing Geological Instrument Factory produced ZSM quartz spring gravimeter with a measuring accuracy of 30 μGal. Eight institutions, including Zhejiang University of Technology and Huazhong University of Science and Technology, have conducted research on ground atomic absolute gravimeter, and the measuring sensitivity has reached 4.2–44.0 μGal/Hz$^{1/2}$. The Institute of Precision Measurement of the Chinese Academy of Sciences has reported a highly integrated atomic absolute gravity gradiometer with an accuracy of less than 1 E and a probe size as small as 92 L. However, both of them are in the prototype development stage, not yet practical.

In the engineering development front of “exploration method for mineral deposits utilizing high-precision ground gravity measurement”, the top two countries in the number of core patents are the USA and China, with a number of 120 and 87, accounting for 35.09% and 25.44% of the total, respectively, and the proportion of patents in other countries is less than 12.00%. In addition, the total number of patents cited in the USA is the highest (2 419), accounting for 44.21% of the total number of citations, while the total number of citations in China and Germany are 17.40% and 11.90%, respectively, and the total number of patents cited in other countries for related technologies is less than 10.00%. The UK has the highest citations per patent (20.25) (Table 2.2.5). In terms of the main institutions of core patents (Table 2.2.6), Infineon Technologies AG (12), TDK Corporation (9), and Robert Bosch Manufacturing Solutions GMBH (9) have more patents. In addition, Hyperfine Research Incorporated has the highest percentage of citations (5.39%) and the highest citations per patent (73.75) (Table 2.2.6). Countries such as Germany, the USA, France, and Switzerland focus on cooperations (Figure 2.2.6). There is no cooperation among major producing institutions.

The traditional spring gravimeter has been developed to the extreme, with little margin for improving the measurement accuracy. As a new generation of quantum gravity sensor, the atomic gravimeter is expected to have a measurement sensitivity of 10^{-4} μGal. However, it is faced with key problems such as miniaturization of atomic gravimeter and improvement of measurement accuracy. In addition, the atomic gravimeter is also faced with problems such as insufficient scale factor and low phase extraction efficiency, which pose enormous challenges to practical application.

The main research fields are the development of miniaturized and high-precision atomic absolute gravimeter/gravity gradiometer, data fine processing, and interpretation, etc., providing higher precision and technologically more advantageous prospecting technology, which has an important practical and strategic significance for building the security of mineral resources of China.

Table 2.2.5 Countries with the greatest output of core patents on "exploration method for mineral deposits utilizing high-precision ground gravity measurement"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	120	35.09	2 419	44.21	20.16
2	China	87	25.44	952	17.40	10.94
3	Germany	40	11.70	651	11.90	16.27
4	Japan	32	9.36	520	9.50	16.25
5	Republic of Korea	12	3.51	156	2.85	13.00
6	Canada	11	3.22	212	3.87	19.27
7	Switzerland	9	2.63	142	2.60	15.78
8	France	8	2.34	126	2.30	15.75
9	Netherlands	6	1.75	69	1.26	11.50
10	UK	4	1.17	81	1.48	20.25

Table 2.2.6 Institutions with the greatest output of core patents on "exploration method for mineral deposits utilizing high-precision ground gravity measurement"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Infineon Technologies AG	12	3.51	245	4.48	20.42
2	TDK Corporation	9	2.63	152	2.78	16.89
3	Robert Bosch Manufacturing Solutions GMBH	9	2.63	132	2.41	14.67
4	Melexis Bulgaria Limited	8	2.34	94	1.72	11.75
5	Allegro MicroSystems	7	2.05	138	2.52	19.71
6	Halliburton Energy Services Incorporation	5	1.46	59	1.08	11.80
7	CNH Industrial Capital Canada Limited	5	1.46	44	0.80	8.80
8	Hyperfine Research Incorporated	4	1.17	295	5.39	73.75
9	Facebook Technologies	4	1.17	91	1.66	22.75
10	United Technologies Corporation	4	1.17	45	0.82	11.25

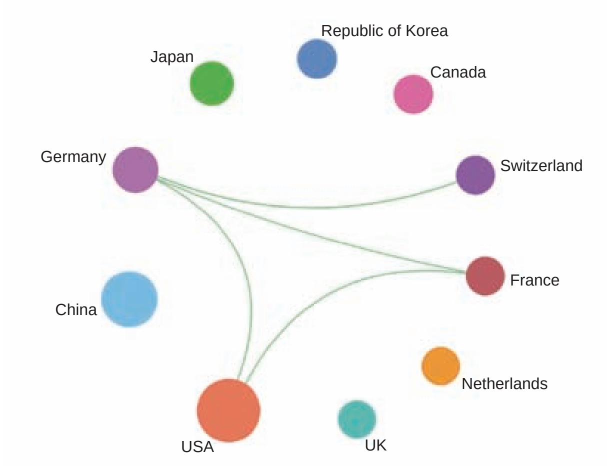

Figure 2.2.6 Collaboration network among major countries in the engineering development front of "exploration method for mineral deposits utilizing high-precision ground gravity measurement"

High precision ground gravity survey technology has broad development prospects in mineral exploration, basic geological research, and other fields (Figure 2.2.7). In the next 5 to 10 years, the key development trend of this technology is the development of practical high-precision atomic absolute gravimeter/gravity gradiometer, accurate terrain correction methods, 3D forward and inversion and geological modeling technology for direct prospecting, and the formation of a rapid and fine measurement of gravity exploration methods and prospecting technology system. At the same time, it is necessary to realize the independent development, miniaturization and practical application of the surface gravimeter, and study the surface gravity and multi-type and multi-source data fusion, well-ground multi-parameter joint constrained inversion, three-dimensional imaging and other gravity processing and interpretation methods to meet the needs of deep mineral resources exploration, better serve the fields of earthquake prevention and national defense construction, which is expected to greatly improve the success rate of prospecting and increase reserves, and enhance social and economic benefits.

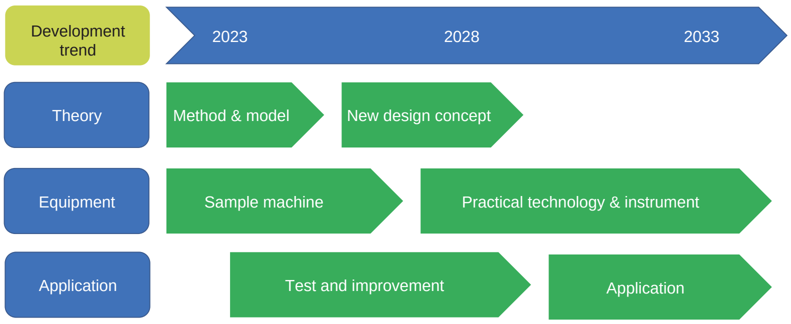

Figure 2.2.7 Roadmap of the engineering development front of “exploration method for mineral deposits utilizing high-precision ground gravity measurement”

2.2.4 Research on intelligent collaborative platform for oil and gas exploration and development

The intelligent collaborative platform for oil and gas exploration and development refers to the provision of an integrated environment that encompasses information sharing, technological innovation, production and operation integration, and intelligent collaboration, facilitating multidisciplinary interaction and integrated exploration and development. In the current wave of oil and gas technological and digital revolutions, the integration of new technologies such as big data and artificial intelligence with the oil and gas industry has become a significant avenue for innovation.

Foreign countries have made initial strides in constructing intelligent collaborative platforms for oil and gas exploration and development. For instance, Akselos deployed digital twins for Shell’s Bonga FPSO, Schlumberger collaborated with Google on the DELFI cloud platform, Total Energies established an integrated oil and gas production collaborative research platform, and Halliburton signed strategic agreements with Accenture and Microsoft. BP and Microsoft also entered into a strategic partnership, while companies like Chevron, Eni, and Abu Dhabi National Oil Company have undertaken intelligent platform research. China’s intelligent collaborative platform development started relatively later and is currently in the transition from digitization to intelligence. China National Petroleum Corporation (CNPC) has developed the “Exploration and Development Dream Cloud” platform, Sinopec has established the “Petrochemical Intelligence Cloud” platform for the energy and chemical industry, and China National Offshore Oil Corporation (CNOOC) is dedicated to creating collaborative working environments and onshore-offshore coordination systems for exploration and development. Although China has achieved preliminary advancements in domestic intelligent collaborative platform construction, overall technology still lags behind foreign counterparts. Currently, the global level of informatization in the oil and gas industry remains relatively low, well below the industry average. In the future, key research directions include the artificial intelligence technology, intelligent oil and gas exploration, integrated geological engineering, intelligent equipment research and development, cloud computing platform construction, and data sharing, etc.

Regarding the engineering development front of “research on intelligent collaborative platform for oil and gas exploration and development”, the major patent-producing countries are China and the USA, with respective publication numbers of 240 and 21, accounting for 87.27% and 7.64%, respectively. The patent publications of other countries related to relevant technologies all account for less than 2.00%. China has the highest citations (441), accounting for 71.36%, while the USA accounts for 26.54%, and other countries all account for less than 5.00%. The USA has the highest citations per patent (7.81), as shown in Table 2.2.7. In terms of patent-producing institutions (Table 2.2.8), major contributors include China Petroleum and Chemical Corporation (12), Southwest Petroleum University (9), China University of Petroleum (Beijing) (8), PetroChina Company Limited (8), China Railway Tunnel Group Company Limited (7), and Central South University (7). Among them, institutions with a percentage

Table 2.2.7 Countries with the greatest output of core patents on “research on intelligent collaborative platform for oil and gas exploration and development”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	240	87.27	441	71.36	1.84
2	USA	21	7.64	164	26.54	7.81
3	Canada	5	1.82	27	4.37	5.40
4	France	5	1.82	27	4.37	5.40
5	Netherlands	5	1.82	27	4.37	5.40
6	Saudi Arabia	5	1.82	5	0.81	1.00
7	India	5	1.82	0	0.00	0.00
8	Russia	2	0.73	4	0.65	2.00
9	Norway	2	0.73	3	0.49	1.50
10	Republic of Korea	1	0.36	6	0.97	6.00

Table 2.2.8 Institutions with the greatest output of core patents on “research on intelligent collaborative platform for oil and gas exploration and development”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China Petroleum and Chemical Corporation	12	4.36	34	5.50	2.83
2	Southwest Petroleum University	9	3.27	12	1.94	1.33
3	China University of Petroleum (Beijing)	8	2.91	16	2.59	2.00
4	PetroChina Company Limited	8	2.91	8	1.29	1.00
5	China Railway Tunnel Group Company Limited	7	2.55	36	5.83	5.14
6	Central South University	7	2.55	20	3.24	2.86
7	Schlumberger Technology Corporation	6	2.18	27	4.37	4.50
8	China National Offshore Oil Corporation	5	1.82	4	0.65	0.80
9	Dalian University of Technology	4	1.45	9	1.46	2.25
10	Shandong University of Science and Technology	4	1.45	5	0.81	1.25

of citations exceeding 5.00% include China Petroleum and Chemical Corporation (5.50%) and China Railway Tunnel Group Company Limited (5.83%). Countries emphasizing cooperation include the USA, the Netherlands, Canada, and France (Figure 2.2.8), with collaborative research between institutions focused on PetroChina Company Limited and Southwest Petroleum University (Figure 2.2.9).

The intelligent collaborative platform for oil and gas exploration and development holds significant prospects in achieving data interconnection, technological exchange, and collaborative research. It is applicable to upstream oil and gas operations such as exploration, drilling, and production. In the next 5 to 10 years, its key development directions include interdisciplinary integration, enhanced data sharing, top-level design, and refined technological architecture.

By organically integrating hardware facilities, software development, digital technology, and oil and gas expertise, a fully digitized, automated, and intelligent professional application environment is expected to be built for the exploration and development process, achieving collaboration in multi-domain in oil and gas exploration and development (Figure 2.2.10). This transformation aims to alter the exploration and development work model, enhance efficiency, maximize comprehensive benefits, and drive the digital transformation and intelligent development of the oil and gas industry.

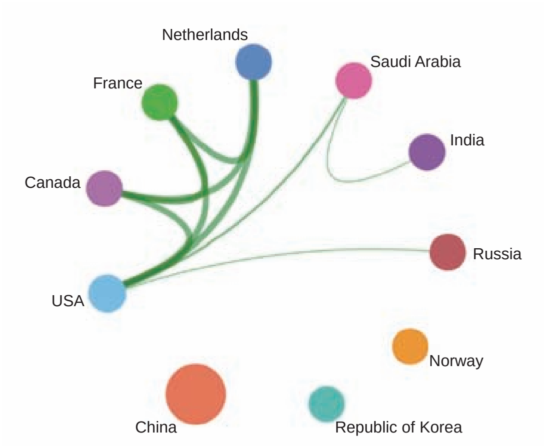

Figure 2.2.8 Collaboration network among major countries in the engineering development front of “research on intelligent collaborative platform for oil and gas exploration and development”

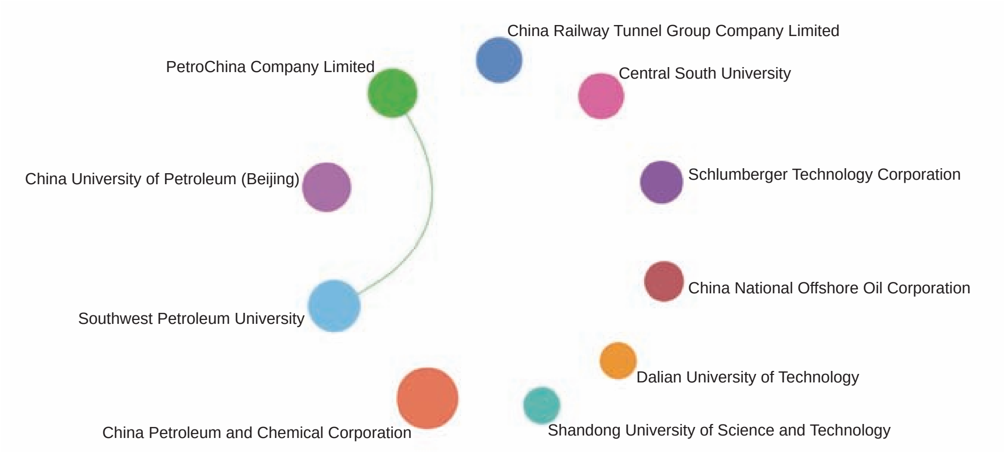

Figure 2.2.9 Collaboration network among major institutions in the engineering development front of “research on intelligent collaborative platform for oil and gas exploration and development”

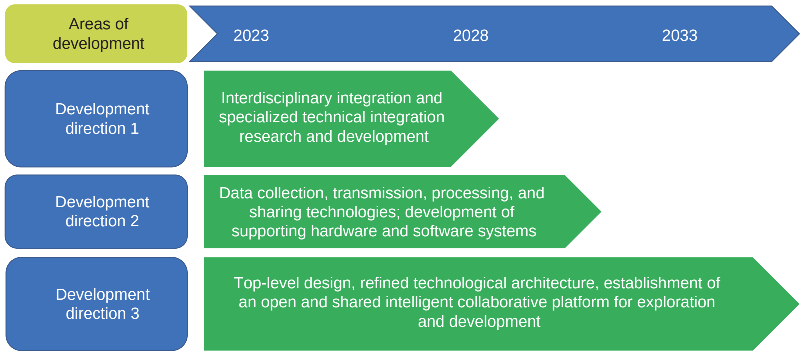

Figure 2.2.10 Roadmap of the engineering development front of "research on intelligent collaborative platform for oil and gas exploration and development"

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V. Civil, Hydraulic, and Architectural Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The Top 10 engineering research fronts in the field of civil, hydraulic, and architectural engineering are summarized in Table 1.1.1. These fronts cover a variety of disciplines, including structural engineering, architectural design and theory, geological engineering, transportation engineering, municipal engineering, hydraulic engineering, urban planning and landscaping, and surveying and mapping engineering. The experts nominated three of these fronts: “performance perception assessment and rehabilitation of in-service road, rail, and airport infrastructure”, “multi-scale spatial optimization of high-density urban built environment guided by safety and resilience”, and “risk identification and control of pathogenic microorganisms in urban water system”. The other seven were identified using the co-citation clustering method applied to the top 10% of highly cited papers, and they were agreed, in expert panel meetings, to be worthy of places in the Top 10. Table 1.1.2 presents annual statistics on the core papers published between 2017 and 2022 that are relevant to these Top 10 research fronts.

(1) AI-based structural damage identification and performance prediction

AI-based structural damage identification and performance prediction is a technology that aims to build intelligent models by integrating cutting-edge information technologies, methods and equipment, such as the Internet of Things, big data, machine learning, etc., for the accurate identification of structural damage and the prediction of performance under different loadings and environmental conditions. It is also possible for the model to conduct self-learning and reinforcement based on fusion of real-time

Table 1.1.1 Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	AI-based structural damage identification and performance prediction	54	3 616	66.96	2020.6
2	Methods and technologies for carbon-emission reduction in urban regeneration	45	2 229	49.53	2020.0
3	Spatio-temporal distribution and intelligent evaluation of giant geological disaster chains	109	6 081	55.79	2019.6
4	Performance perception assessment and rehabilitation of in-service road, rail, and airport infrastructure	25	852	34.08	2019.9
5	Life-cycle disaster resilience of structural and engineering systems	37	1 456	39.35	2020.8
6	Co-fermentation of municipal sludge and refuse for efficient resource utilization	73	3 012	41.26	2020.0
7	Coordinated evolution of groundwater quantity, quality and environmental impact and groundwater sustainable utilization	72	5 307	73.71	2020.1
8	Multi-scale spatial optimization of high-density urban built environment guided by safety and resilience	16	681	42.56	2020.3
9	Risk identification and control of pathogenic microorganisms in urban water systems	17	816	48.00	2019.4
10	Intelligent object detection in high-resolution remote sensing images	151	14 846	98.32	2020.2

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in civil, hydraulic, and architectural engineering

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	AI-based structural damage identification and performance prediction	1	3	8	9	19	14
2	Methods and technologies for carbon-emission reduction in urban regeneration	5	5	8	6	11	10
3	Spatio-temporal distribution and intelligent evaluation of giant geological disaster chains	17	18	14	21	22	17
4	Performance perception assessment and rehabilitation of in-service road, rail, and airport infrastructure	3	3	6	2	4	7
5	Life-cycle disaster resilience of structural and engineering systems	1	2	5	6	4	19
6	Co-fermentation of municipal sludge and refuse for efficient resource utilization	1	1	2	1	6	2
7	Coordinated evolution of groundwater quantity, quality and environmental impact and groundwater sustainable utilization	11	5	9	10	14	23
8	Multi-scale spatial optimization of high-density urban built environment guided by safety and resilience	1	0	3	4	5	3
9	Risk identification and control of pathogenic microorganisms in urban water systems	5	4	6	5	1	4
10	Intelligent object detection in high-resolution remote sensing images	11	15	18	38	29	40

data from structural responses and from radar/vision/sound sensors. The research on AI-based structural damage identification and performance prediction is of great significance, as it can improve the functionality, economy, reliability and safety of structures during their life cycles. The major topics covered by this research front include: ① new sensing equipment for structural damage detection and monitoring; ② standardization and fusion of structural health monitoring data; ③ structural damage detection and localization based on machine learning algorithms; ④ data-driven structural performance prediction methods; and ⑤ physics-informed intelligent models for structural performance prediction. The main development trend is to build a system for the holographic perception of structural status and providing intelligent diagnosis, and to improve ability in structural damage identification and performance prediction models in terms of interpretability, generalization, accuracy, etc. With the integration of physical information and prior knowledge, models can be evolved and widely applied in engineering projects in complex scenarios. Between 2017 and 2022, 54 core papers relevant to this research front were published. These papers received 3 616 citations, with an average of 66.96 citations per paper.

(2) Methods and technologies for carbon-emission reduction in urban regeneration

The methods and techniques for carbon-emission reduction in urban regeneration primarily refer to the integration of strategies to reduce carbon emissions relating to urban renewal design. These methods and techniques introduce carbon-emission reduction approaches and technologies into the process of updating various urban elements, thereby significantly promoting low-carbon development and sustainability in cities. The primary technological directions encompass: ① simulation of energy consumption and microclimate environments in existing urban areas; ② optimization of urban regeneration design schemes and decision-making tools that are subject to carbon reduction goals; ③ integration of carbon-emission reduction technologies with building materials and innovative construction techniques in urban regeneration; and ④ integrated design of carbon-emission reduction technologies for diverse types and scales of urban regeneration elements. The development trend in the field involves integrating interdisciplinary knowledge such as building energy-saving technologies, renewable energy technologies, geographic information science, computer science, and artificial intelligence. This integration facilitates the blending of urban regeneration elements with carbon-emission reduction technologies. Furthermore, the development of digital platforms allows for multi-scenario simulations, application, and monitoring feedback, effectively supporting sustainable and organic urban regeneration. Between 2017 and 2022, 45 core papers relevant to this research front were published. These papers received 2 229 citations, with an average of 49.53 citations per paper.

(3) Spatio-temporal distribution and intelligent evaluation of giant geological disaster chains

The giant geological disaster chain refers to a series of geological disaster events, which include one or more secondary disasters induced by an initial event, directly or indirectly. Compared to a single geological disaster, a giant geological disaster chain shows significant uncertainty. It features a complex formation mechanism with multiple disasters affecting each other and a disaster-enlarging effect caused by the chain-like cumulative amplification process. In recent years, the engineering constructions in high-altitude and cold regions in China, represented by the Sichuan-Tibet Railway, have been facing the threat of giant geological disaster chains. The disaster scale has reached hundreds of millions cubic meters and serious casualties and economic losses have resulted. Accurately predicting the spatio-temporal distribution of such chains and intelligently assessing their ongoing disaster risks is crucial for ensuring the safety, economy, and sustainability of engineering constructions. The current research focuses on: ① spatio-temporal distribution characteristics and intelligent identification of geological disaster chains in complex disaster prone environments; ② formation and evolution mechanism of geological disaster chains and establishment of dynamic models; ③ resilience and risk assessment and optimization methods for preventive structures of geological disaster chains; and ④ real time monitoring and warning, intelligent evaluation and response to preventive decisions for large-scale giant geological disaster chains. The development trend involves distinguishing the spatio-temporal distribution pattern of giant geological disaster chains and clarifying the catastrophe mechanism. On this basis, multi-source data and intelligent algorithms can be integrated to predict the development trend of geological disaster chains and to assess potential risks and impacts. Meanwhile, a real-time monitoring and early warning system needs to be developed based on intelligent technology. At last, an intelligent risk assessment, prevention, control and decision-making system should be built for large-scale and giant geological disaster chains. Between 2017 and 2022, 109 core papers relevant to this research front were published. These papers received 6 081 citations, with an average of 55.79 citations per paper.

(4) Performance perception assessment and rehabilitation of in-service road, rail, and airport infrastructure

The assessment and rehabilitation of in-service road, rail, and airport infrastructure involve the utilization of intelligent perception technologies and comprehensive evaluation methodologies for real-time monitoring, assessment, and prediction of the performance status of existing transportation infrastructure such as roads, railway tracks, and airport facilities. This is essential for accommodating the growing demand for passenger and freight transportation by facilitating necessary improvements and expansions to enhance safety, reliability, and sustainability of transportation infrastructure and adapt to the continually evolving environment and user needs. Compared to new infrastructure development, repair and expansion of in-service road, rail, and airport projects are confronted with more intricate temporal, spatial, and ecological constraints. Research directions within this field encompass the following: ① structural health monitoring and assessment, i.e., utilizing sensor technologies, non-destructive testing methods, and other tools to perform real-time monitoring and comprehensive assessment in order to detect potential structural issues, prevent accidents with efficient and precise assessment, and enhance structural and functional durability; ② traffic load perception and optimization, i.e., leveraging intelligent transportation systems, with big data analytics, and related methodologies to real-time perceived traffic flows for accurate traffic management and scheduling; ③ environmental assessment and enhancement, i.e., monitoring and analyzing factors such as climate and geology to study the impact of traffic loads and environmental changes on structures for optimizing the design and maintenance strategies of transportation infrastructure and ultimately enhancing durability and adaptability; and ④ rehabilitation and expansion planning and design, i.e., integrating analysis of structural in-service state evolution patterns and performance perception assessment to formulate rational plans for facility rehabilitation and expansion, aligning with future transportation development demands. Future developments in this field are anticipated to concentrate on the following areas: high-precision intelligent perception and assessment; sustainability and environmentally friendly low-carbon design; comprehensive performance optimization algorithms and decision models; digital construction and engineering management. Between 2017 and 2022, 25 core papers relevant to this research front were published.

These papers received 852 citations, with an average of 34.08 citations per paper.

(5) Life-cycle disaster resilience of structural and engineering systems

The life-cycle disaster resilience of structural and engineering systems refers to the evaluation and improvement of their resilience to natural and man-made disasters throughout their entire life cycle, including design, construction, maintenance, and demolition. Traditional research on disaster resilience of structural and engineering systems is mainly focused on design and construction stages, with less attention paid to maintenance and demolition stages. As a great number of structural and engineering systems accumulate in various countries around the world, research on disaster resilience of existing structural and engineering systems has significant social significance and strategic value for the construction of resilient cities. Its main research directions include: ① assessment of life-cycle disaster resistance and resilience improvement of a single structure; ② assessment and improvement of disaster resilience of building systems throughout their entire lifespan; ③ assessment and improvement of disaster resilience of lifeline systems such as water, electricity, gas and communication networks; and ④ construction of resilient cities with multiple systems for considering disaster resilience throughout infrastructure lifespan. The main development trend for future research relates to the life-cycle damage mechanism, resilience assessment and resilience improvement for complex and giant systems. Based on this, combined with health monitoring, big data and artificial intelligence, accurate assessment and significant improvement of the life-cycle disaster resilience of urban engineering systems can be achieved. At the same time, the development of intelligence of urban engineering system resilience and disaster prevention can be accelerated, and the disaster resistance safety of urban engineering systems can be improved. This will also lead to establishment of a resilient disaster prevention and control system for the entire lifespan of urban engineering systems. Between 2017 and 2022, 37 core papers relevant to this research front were published. These papers received 1 456 citations, with an average of 39.35 citations per paper.

(6) Co-fermentation of municipal sludge and refuse for efficient resource utilization

Municipal sludge is the inevitable product of municipal sewage treatment, with the dual attributes of “pollution” and “resource”. Harmless treatment and resource utilization of sludge are the key measures for promotion of the synergy between pollution control and carbon-emission reduction in the field of water pollution prevention and control. The collaborative anaerobic fermentation treatment of municipal sludge and organic wastes such as refuse can produce significant economic and environmental benefits, which is conducive to improving the degradation efficiency of organic matter and the stability of fermentation systems, and significantly increasing the output of high-value products. Thus, the co-fermentation of municipal sludge and refuse is an effective way to realize the harmless treatment and resource utilization of municipal sludge. The current research focuses on: ① the co-fermentation mechanism and resource efficiency of municipal sludge and refuse under different conditions; ② optimization and control technology of municipal sludge and refuse co-fermentation; ③ the high-value directional transformation mechanism of municipal sludge and refuse co-fermentation; and ④ research and development of municipal sludge and waste co-fermentation equipment. The main development trend in the future is gradual clarification of the influencing factors regarding urban sludge and waste co-fermentation efficiency and energy consumption. On this basis, attention is placed on optimization of the resource path of the municipal sludge and refuse co-fermentation process, strengthening the production of new clean biofuels in the co-fermentation process, further reducing the cost of co-fermentation, and building an efficient resource technology and equipment system of municipal sludge and refuse co-fermentation. Between 2017 and 2022, 73 core papers relevant to this research front were published. These papers received 3 012 citations, with an average of 41.26 citations per paper.

(7) Coordinated evolution of groundwater quantity, quality and environmental impact and groundwater sustainable utilization

Groundwater plays a critical role in the urban and rural water supply, economic and social development, and ecological and environmental maintenance in China. The coordinated progress relating to groundwater quantity, quality and environmental impact concerns the interactions and change in groundwater resources, involving water quality and ecological and geological environmental effects. The sustainable utilization of groundwater is aimed at ensuring that groundwater resources can meet the long-term stable development of human society and the whole environmental system, and can avoid ecological and geological problems and disasters caused by over-exploitation. China’s groundwater resources are under great threat due to increased human activity and climate change. The current research focuses on: ① theoretical research of groundwater circulation and distribution, and pollutant migration and transformation; ② development of methodology of groundwater monitoring-simulation-evaluation; ③ technological investigation of groundwater over-exploitation prevention and groundwater remediation; and ④ management of sustainable utilization of groundwater. Future development trends include the following: ① addressing the challenging theoretical task of groundwater circulation as well as the migration and transformation of material and energy in a changing environment; ② developing new methods for air-space-ground integrated groundwater monitoring and interpretation; ③ establishing multi-scale multi-process technical systems for groundwater simulation and prediction and groundwater quantity-quality-environmental impact evaluation; ④ to exploring key technologies for warning, control and prevention of groundwater over-exploitation and its secondary disasters; ⑤ completing key technical challenges on contamination source identification and ecological restoration; ⑥ creating multi-source groundwater storage and sustainable utilization technologies in the continent and ocean; and ⑦ proposing multi-objective optimization management system for different scenarios and groundwater resource regulation measurements and strategies. Between 2017 and 2022, 72 core papers relevant to this research front were published. These papers received 5 307 citations, with an average of 73.71 citations per paper.

(8) Multi-scale spatial optimization of high-density urban built environment guided by safety and resilience

The high-density urban built environment, guided by requirements for safety and resilience, concerns urban planning and design that prioritizes the creation of a living environment that is both secure, disaster-resistant, and sustainable under conditions of high population density. Unlike conventional cities, high-density cities face distinct challenges such as heightened safety risks associated with high-risk buildings, suboptimal performance of disaster-resistant building, low standards of evacuation of buildings, and inadequate building maintenance systems. In recent years, China's increased frequency of extreme weather and climate events, has subjected the country's high-density urban disaster prevention systems to rigorous testing. Consequently, the safety and resilience of high-density urban development have formed the basis of a critical research trend. It is of great importance to explore typical disaster scenarios related to high-risk, disaster-resistant, and disaster-avoidance buildings and bolstering urban resilience to effectively manage the profound impacts of climate change. The current research focuses on: ① reevaluation and reformulation of building codes tailored to high-density cities; ② ongoing dynamic monitoring and assessment of buildings within high-density urban areas; ③ enhancement of the resilience and sustainability of buildings in high-density environments; ④ the renewal and renovation of high-density urban building stocks; and ⑤ optimizing disaster resilience in high-density urban and rural built environments within land-sea integrated regions. The development trend of research is to identify vulnerabilities and to gauge the quality of the built environment in high-density cities. On this basis, a combination of research into safety hazards and resilience, coupled with multi-scale analysis and predictive assessment of the myriad risks inherent in mega-city environments, will drive the optimization of high-density urban settings from the perspective of sustainable development. Advanced methodologies like deep learning, data mining, and digital twin technology will be harnessed for this purpose. Between 2017 and 2022, 16 core papers relevant to this research front were published. These papers received 681 citations, with an average of 42.56 citations per paper.

(9) Risk identification and control of pathogenic microorganisms in urban water systems

Urban water environment is closely related to natural circulation and human production activities. There are risks of outbreak and spread of pathogenic microorganisms such as pathogens and viruses in urban water system, mainly from human and animal feces, garbage, domestic sewage and hospital sewage. The migration and spread of pathogenic microorganisms in urban water systems can lead to outbreak of epidemic diseases, posing a serious threat to environmental safety and public health. Effective identification, control, and deep reduction of pathogenic microorganisms in urban water systems, as well as ensuring water safety, are urgent issues that need to be addressed. The main technical directions include: ① building a basic database of the specific types, distribution, transmission patterns, and removal pathways of pathogenic microorganisms in urban rivers/lakes; ② rapid identification, characterization, and risk assessment of pathogenic microorganisms in the water quality monitoring and evaluation system; ③ the inactivation of pathogenic microorganisms by conventional disinfection techniques (chlorine based disinfectants, ozone, UV, etc.) and combined disinfectants; ④ development of novel membrane separation technologies and adsorbents based on the principles of physical separation and adsorption; ⑤ microbial metabolism technologies such as activated sludge process, membrane bio-reactor (MBR) process, etc.; and ⑥ progress towards a comprehensive risk management and control technology system for pathogenic microorganisms, including water source control, water plant removal, and pipeline network protection. Facing the ecological security of urban water systems, future research focuses and challenges mainly include building a database of resistance groups/pathogens/pathogenic viruses in typical water systems, developing a list of water borne pathogenic microorganisms for priority control in river basins, establishing indicative pathogenic microorganisms for health risk assessment, developing high-throughput detection methods with supporting equipment, and establishing a comprehensive control technology system. Between 2017 and 2022, 17 core papers relevant to this research front were published. These papers received 816 citations, with an average of 48.00 citations per paper.

(10) Intelligent object detection in high-resolution remote sensing images

Intelligent object detection methods in high-resolution remote sensing images utilize knowledge engineering, deep learning, logical reasoning, swarm intelligence, and other new artificial intelligence technologies and means, to obtain category and location information from high-resolution remote sensing images. Such technologies are widely used in military and civilian fields such as reconnaissance, surveillance, early warning, and search and rescue. Development trends in this research front include: ① general intelligent target detection methods, which aim to address the challenges faced in remote sensing image target detection, such as class imbalance, high background complexity, multi-scale changes in targets, special imaging perspectives, and small/micro object detection; and ② development of specialized object intelligent detection methods in remote sensing images for significant targets such as airports, buildings, aircraft, ships, vehicles, clouds, and sea ice. The main development trend in the future will be a focus on the challenges of small object detection and multimodal object detection, continuously optimizing the intelligent object detection model, constructing an intelligent high-resolution remote sensing object detection method system guided by knowledge and based on algorithms, thereby promoting intelligent understanding of remote sensing scenes and providing support for the construction of remote sensing image intelligent interpretation systems. Between 2017 and 2022, 151 core papers relevant to this research front were published. These papers received 14 846 citations, with an average of 98.32 citations per paper.

1.2 Interpretations for three key engineering research fronts

1.2.1 AI-based structural damage identification and performance prediction

The damage of civil engineering structures is related to their health status, and directly affects their safety and serviceability. Traditional methods of structural damage identification and performance prediction usually rely on physical sensors and mechanical models, while using AI methods can extract complex damage feature patterns from large amounts of multi-source multi-modal data, and analyze the key parameters that characterize structural performances. Additionally, the model can perform self-learning and reinforcement based on real-time data, to improve the accuracy and robustness of the results in damage identification and performance prediction. The research on AI-based structural damage identification and performance prediction can provide a scientific basis for structural health monitoring, maintenance reinforcement and performance enhancement. This is of great significance in reducing infrastructure operation and maintenance costs, improving management and maintenance strategies, and optimizing the life-cycle design of structures. The major topics in this research field include:

1) New sensing equipment for structural damage detection and monitoring. Efforts are devoted to: ① achieving qualitative perception and quantitative determination of structural damage in different scenarios and scales using various sensing technologies, such as visual and acoustic sensors, microwave radar, distributed Fiber Bragg Grating, nanomaterial sensors, etc.; ② developing new integrated equipment and the corresponding distributed intelligence technology for structural damage detection and monitoring; and ③ establishing intelligent structural damage detection and monitoring systems that are capable of serving in an

autonomous, comprehensive, and efficient way.

2) Standardization and fusion of structural health monitoring data. For the development of AI algorithms and model optimization, studies are carried out to establish the standard for the acquisition, transmission, storage, and usage of structural monitoring data. Technologies such as knowledge graphs, Bayesian networks, probabilistic graphical models, etc., are applied for the aggregation of multi-source and multi-scale data, providing high-availability data for structural damage identification and performance prediction.

3) Structural damage detection and localization based on machine learning algorithms. Based on machine learning models such as deep learning, support vector machine, clustering algorithm, etc., the damage mechanism is studied and surrogate models are built for structural damage detection and localization. Meanwhile, the models are iterated autonomously for self-learning and reinforcement using real-time data for environmental and structural concerns, thereby improving the accuracy and reliability of damage identification.

4) Data-driven prediction methods of structural performance. Considering the complex influencing factors of performances and the scarce data feature of engineering structures, data processing methods are proposed for feature extraction and feature analysis, and the data dimension is reduced effectively and efficiently. By combining active learning, reinforcement learning, and transfer learning, data-driven models relating to key characteristic parameters are established to predict various aspects of structural performances, including the mechanical performance, disaster prevention and mitigation resilience, and life cycle performance.

5) Physics-informed intelligent models for structural performance prediction. By the development of data, knowledge, models, and intelligent algorithms, mechanical theories and experts' priori knowledge can be introduced to propose a hybrid paradigm of physics-informed intelligent modeling for structural performance prediction. It is important for AI models to break through the bottleneck of the data dependency of model training and the deficiency in interpretability and generalization ability due to the "black box". Such a breakthrough can drastically improve the accuracy and practicability of the data-driven model for performance prediction on engineering structures.

As shown in Table 1.1.1, 54 core papers concerning "AI-based structural damage identification and performance prediction" were published between 2017 and 2022, with each paper being cited 66.96 times on average. The top five countries in terms of output of core papers on this topic are Vietnam, Belgium, China, Republic of Korea, and the USA (Table 1.2.1). China is one of the most active countries, having published 25.93% of the core papers. The five countries with the highest average citations were the USA, Algeria, Belgium, Vietnam, and Japan. The papers published by Chinese authors were cited 66.36 times on average, which is slightly below the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.1, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were Ghent University, Ton Duc Thang University, Ho Chi Minh City Open University, Southeast University, and University of Transport & Communications (Table 1.2.2). In terms of number of publications, the top three institutions collaborated frequently, focusing on AI models for structural damage identification. They proposed various algorithms to solve the inverse problems in structural health monitoring, i.e. identifying structural damage based on responses such as structural stiffness, frequencies, and strain energy, etc. Their research primarily applies to laminated composite structures, and is also applicable in actual bridges. As illustrated in Figure 1.2.2, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 1.2.3, the five most active countries in terms of paper citing were China, the USA, Vietnam, Republic of Korea, and Iran. The top five institutions in terms of citing core papers were Tongji University, Southeast University, Ghent University, Ho Chi Minh City Open University, and Harbin Institute of Technology (Table 1.2.4). According to the citations of core papers, there were differences between the top five countries in terms of output of core papers and the five most active countries in terms of paper citations, which indicates that this front has received attention from scholars from different countries.

Based on the above statistics, the proportion of paper citations in China is far higher than the proportion of core papers from China, indicating that Chinese researchers pay close attention to this front.

In the next ten years, the key development direction in this research front is to build a holographic perception system for structure status, to establish a structure intelligent diagnosis system driven by multi-modal large models and to enhance model performance for structural damage identification and performance prediction. On one hand, these developments rely on highly-integrated intelligent perception technology, combined with multi-source multi-modal data fusion modeling, which significantly improves the capacity and quality of available data. On the other hand, the damage mechanism and performance evolution process of structures under multi-factor multi-objective conditions can be taken into account for the exploration of the new paradigm that combines knowledge-driven learning models and physics information. Hence, it can achieve the improvement of structural damage identification and performance prediction in terms of interpretability, generalization, accuracy, etc. Relevant research studies can be applied to the operation and maintenance of existing structures, as well as to the design and construction of new structures, thus there is a great potential of development and a wide range of practical scenarios (Figure 1.2.3).

Table 1.2.1 Countries with the greatest output of core papers on "AI-based structural damage identification and performance prediction"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Vietnam	22	40.74	1 607	73.05	2020.2
2	Belgium	20	37.04	1 585	79.25	2020.0
3	China	14	25.93	929	66.36	2020.9
4	Republic of Korea	14	25.93	913	65.21	2020.9
5	USA	10	18.52	1 041	104.10	2020.2
6	Algeria	10	18.52	900	90.00	2020.2
7	Japan	6	11.11	430	71.67	2020.0
8	Italy	6	11.11	266	44.33	2020.2
9	Canada	5	9.26	289	57.80	2021.2
10	India	4	7.41	279	69.75	2021.2

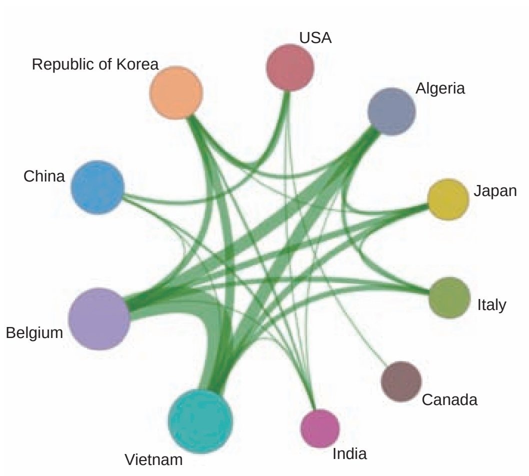

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "AI-based structural damage identification and performance prediction"

Table 1.2.2 Institutions with the greatest output of core papers on "AI-based structural damage identification and performance prediction"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Ghent University	20	37.04	1 585	79.25	2020.0
2	Ton Duc Thang University	13	24.07	1 192	91.69	2019.5
3	Ho Chi Minh City Open University	8	14.81	500	62.50	2021.2
4	Southeast University	8	14.81	380	47.50	2021.2
5	University of Transport & Communications	7	12.96	499	71.29	2020.0
6	Chang'an University	6	11.11	256	42.67	2021.3
7	University of California, Los Angeles	4	7.41	393	98.25	2019.8
8	Hanyang University	4	7.41	351	87.75	2020.2
9	Mouloud Mammeri University of Tizi-Ouzou	4	7.41	319	79.75	2020.5
10	Tongji University	4	7.41	315	78.75	2020.5

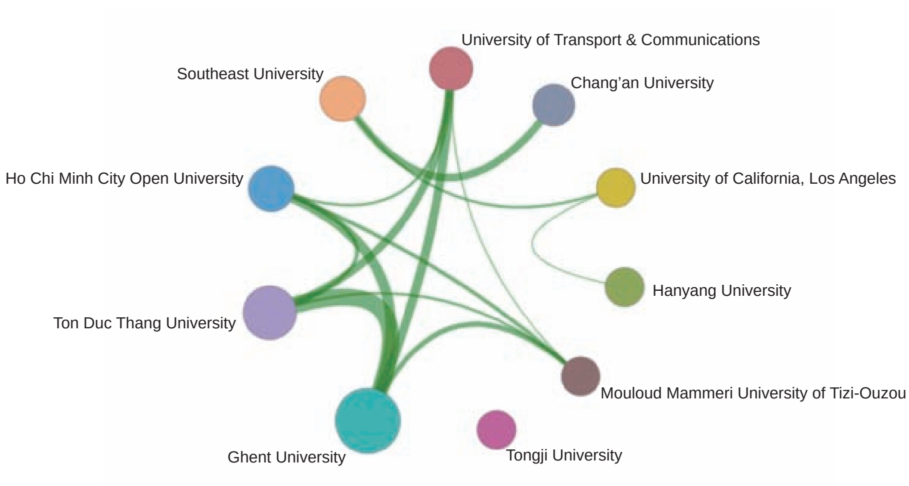

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "AI-based structural damage identification and performance prediction"

Table 1.2.3 Countries with the greatest output of citing papers on "AI-based structural damage identification and performance prediction"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	868	40.07	2021.7
2	USA	235	10.85	2021.5
3	Vietnam	169	7.80	2021.4
4	Republic of Korea	144	6.65	2021.6
5	Iran	142	6.56	2021.6
6	India	138	6.37	2021.7
7	Italy	105	4.85	2021.7
8	Australia	102	4.71	2021.7
9	Canada	99	4.57	2021.7
10	Saudi Arabia	87	4.02	2021.6

Table 1.2.4 Institutions with the greatest output of citing papers on "AI-based structural damage identification and performance prediction"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Tongji University	95	17.66	2021.7
2	Southeast University	87	16.17	2021.7
3	Ghent University	74	13.75	2021.0
4	Ho Chi Minh City Open University	43	7.99	2021.7
5	Harbin Institute of Technology	41	7.62	2021.8
6	The Hong Kong Polytechnic University	40	7.43	2021.9
7	Ton Duc Thang University	36	6.69	2020.5
8	Dalian University of Technology	33	6.13	2021.7
9	Yonsei University	31	5.76	2021.7
10	University of Transport & Communications	30	5.58	2020.8

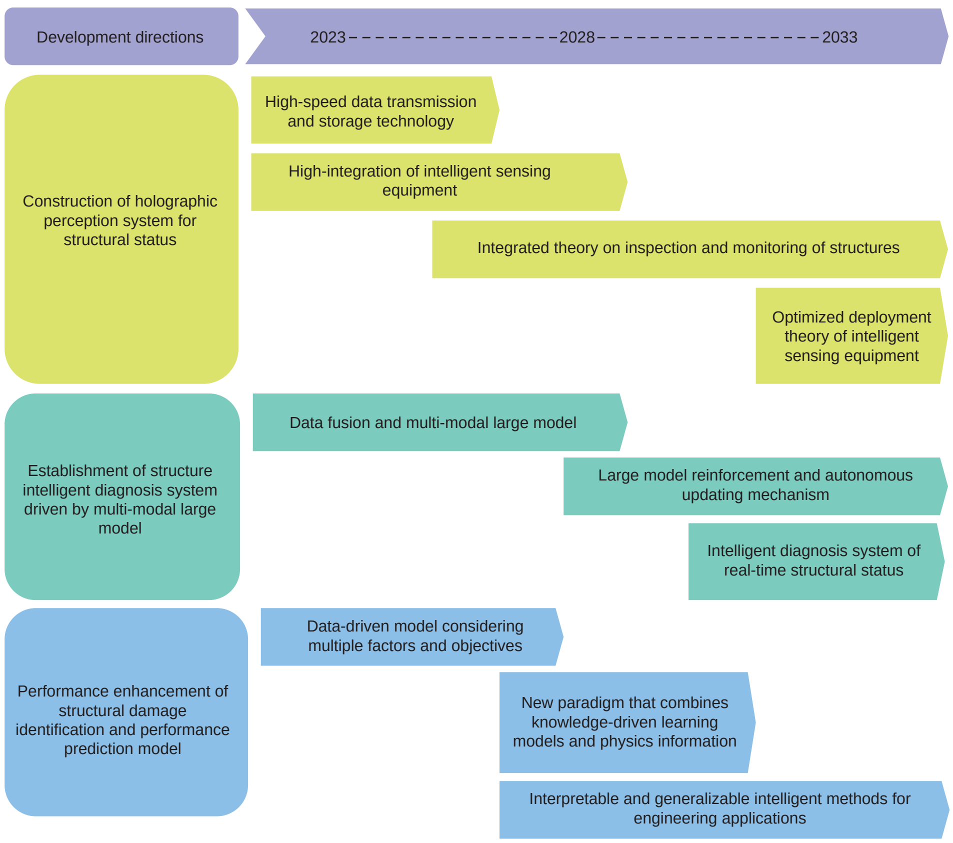

Figure 1.2.3 Roadmap of the engineering research front of "AI-based structural damage identification and performance prediction"

1.2.2 Methods and technologies for carbon-emission reduction in urban regeneration

Urban regeneration, optimizing the physical conditions, spatial forms, and functions of the entire urban system, plays a crucial role in improving the currently high-energy consumption and high-carbon-emitting components of cities. It offers pivotal intervention for reducing urban carbon dioxide emissions. However, the current approach to urban regeneration primarily relies on traditional models, which face challenges such as difficulty in integrating urban regeneration targets with carbon-emission reduction technologies, limited perspectives on integration, low digital precision, and a lack of practical applications.

Therefore, the forefront and focus of research and development in urban regeneration methods and technologies lie in establishing systematic integration and collaborative mechanisms for applying various carbon-emission reduction technologies in urban regeneration. This involves exploring methods utilizing machine learning, genetic algorithms, and other techniques to optimize design and decision-making processes, as well as innovation of the integration of high-performance building materials with carbon-emission reduction technologies. The primary technological directions encompass:

1) Simulation of energy consumption and microclimate environment in existing urban areas. This involves leveraging extracted building big data information and relevant standard specifications, combined with GIS and building energy simulation tools, to automatically generate regional models of building energy consumption and carbon emissions. These models enable rapid modeling at the regional scale and can be automatically calibrated based on real-world data.

2) Optimization of urban regeneration design schemes and decision-making tools under carbon reduction goals. This involves utilizing advanced technologies and methods such as machine learning, big data analytics, and genetic algorithms to develop systems and platforms for scenario simulation and low-carbon assessment. These systems and platforms identify the current carbon dioxide emissions status and reduction potential of different urban regeneration measures, and generate the most suitable urban regeneration schemes through multi-objective optimization.

3) Integration of carbon-emission reduction technologies with building materials and innovative construction techniques in urban regeneration. The construction industry is considered a major consumer of raw materials and energy. In the maintenance and renovation of existing buildings and infrastructure, the application of high-performance building materials and innovative construction techniques integrated with carbon-emission reduction technologies can prove advantageous in addressing the challenges of low energy efficiency and high carbon emissions faced by the construction industry.

4) Integrated design of carbon reduction technologies for diverse types and scales of urban regeneration elements. Urban regeneration involves comprehensive and complex system engineering projects. In addition to in-depth research on the application of carbon-emission reduction technologies to individual urban regeneration elements, it is essential to establish the coupling of emission reduction technologies to utilization by various urban elements. This includes areas such as energy, buildings, transportation, waste management, and carbon sequestration techniques.

As shown in Table 1.1.1, 45 core papers concerning "methods and technologies for carbon-emission reduction in urban regeneration" were published between 2017 and 2022, with each paper being cited 49.53 times on average. The top five countries in terms of output of core papers on this topic are China, the USA, the UK, Italy, and Australia (Table 1.2.5). China is the most active country, having published 55.56% of the core papers. The five countries with the highest citations per paper were China, Australia, the USA, Singapore, and Israel. The papers published by Chinese authors were cited 62.40 times on average, which is above the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.4, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were China University of Mining & Technology, East China Normal University, Wuhan University, Shanghai Jiao Tong University, and University of Shanghai for Science and Technology (Table 1.2.6). The forefront directions at China University of Mining and Technology primarily include research on the development of renewable energy, smart city policies, and industrial integration to enhance energy efficiency, reduce carbon emissions, and mitigation of the impact of air pollution. This research aims to provide empirical evidence and policy insights. At East China Normal University, the forefront directions mainly involve studying the spatio-temporal variations of CO_2 from a multi-scale perspective and examining the impact of government policies on ecological efficiency. This research aims to provide scientific foundations for feasible CO_2 emission reduction policies. At Wuhan University, the forefront directions focus on studying the distribution characteristics and deployment potential of different renewable energy sources, as well as the influencing mechanisms on their power generation efficiency. Additionally, attention is given to the spatio-temporal distribution patterns of PM2.5, CO_2, and their influencing factors. As illustrated in Figure 1.2.5, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 1.2.7, the five most active countries in terms of citations were China, the USA, the UK, Australia, and Italy. The top five institutions in terms of citations were Chinese Academy of Sciences, China University of Mining & Technology, Chongqing University, Wuhan University, and Tsinghua University (Table 1.2.8). China ranked first in the quantity of core papers produced and the number of citations of core papers, indicating that Chinese researchers pay close attention to this front.

Summarizing the above statistics, Chinese scholars have performed well and become leaders in the research of "methods and technologies for carbon-emission reduction in urban regeneration".

The key development directions for the forefront of "Methods and technologies for carbon-emission reduction in urban regeneration" in the next 5–10 years will be as follows: the development and application of carbon reduction materials in urban regeneration; integration of new energy and building technologies; optimization of low-carbon design in urban regeneration; integration of carbon-emission reduction technologies; application of digital technologies and verification of carbon-emission reduction effectiveness.

Specifically, in the construction and computation of energy consumption and carbon emissions simulations, efforts will be made to improve the accuracy of precise accounting and dynamic prediction of carbon emissions from urban-scale building clusters, catering to different scales of urban regeneration design.

In terms of technology integration and application, there will be a focus on promoting iterative updates of individual carbon-emission reduction engineering technologies in urban and neighborhood renewal projects, while establishing integrated carbon-emission reduction technologies for multi-system coupling in urban regeneration projects.

Regarding the development of decision support tools for low-carbon urban regeneration, the emphasis will be on establishing comprehensive platforms for optimizing solutions with various emission reduction technologies, and clarifying the "low-carbon" goals, indicators, and technological pathways for different regions and stages of urban development (Figure 1.2.6).

Table 1.2.5 Countries with the greatest output of core papers on "methods and technologies for carbon-emission reduction in urban regeneration"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	25	55.56	1 560	62.40	2020.3
2	USA	5	11.11	258	51.60	2021.2
3	UK	4	8.89	157	39.25	2021.0
4	Italy	4	8.89	65	16.25	2019.2
5	Australia	3	6.67	171	57.00	2018.0
6	Singapore	3	6.67	130	43.33	2017.7
7	Germany	3	6.67	122	40.67	2019.3
8	Bangladesh	3	6.67	98	32.67	2022.0
9	Malaysia	3	6.67	98	32.67	2022.0
10	Israel	2	4.44	84	42.00	2019.0

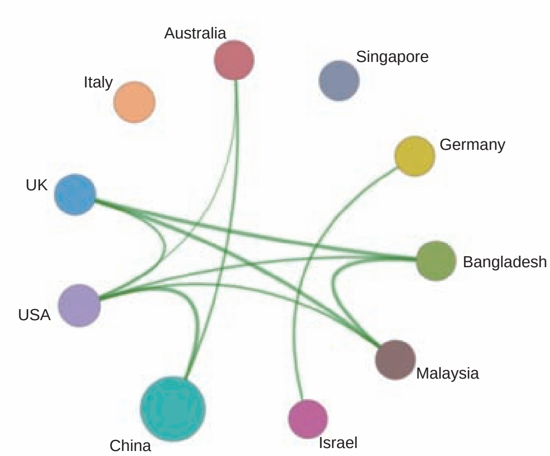

Figure 1.2.4 Collaboration network among major countries in the engineering research front of "methods and technologies for carbon-emission reduction in urban regeneration"

Table 1.2.6 Institutions with the greatest output of core papers on "methods and technologies for carbon-emission reduction in urban regeneration"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China University of Mining & Technology	6	13.33	327	54.50	2021.7
2	East China Normal University	4	8.89	311	77.75	2018.2
3	Wuhan University	4	8.89	244	61.00	2019.5
4	Shanghai Jiao Tong University	4	8.89	212	53.00	2020.0
5	University of Shanghai for Science and Technology	4	8.89	212	53.00	2020.0
6	Chongqing University	3	6.67	202	67.33	2021.3
7	Hebei University of Technology	3	6.67	202	67.33	2021.3
8	Technical University of Munich	3	6.67	122	40.67	2019.3
9	Khulna University of Engineering and Technology	3	6.67	98	32.67	2022.0
10	Rajshahi University of Engineering and Technology	3	6.67	98	32.67	2022.0

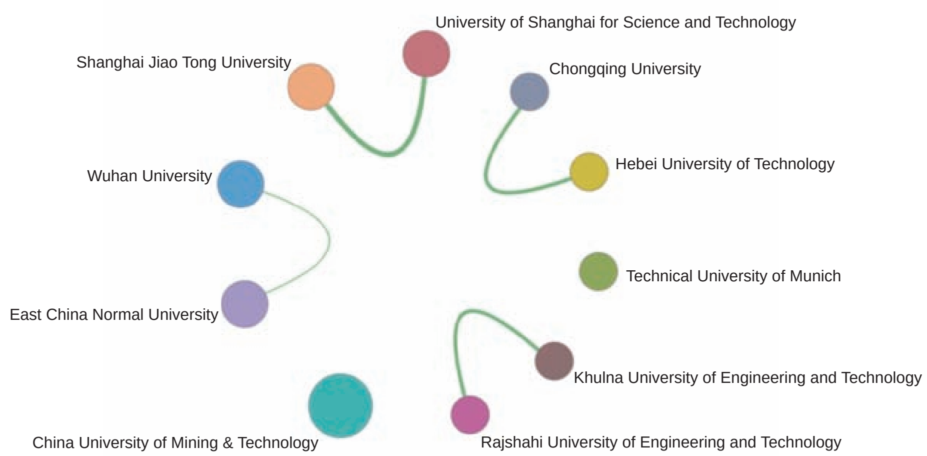

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "methods and technologies for carbon-emission reduction in urban regeneration"

Table 1.2.7 Countries with the greatest output of citing papers on "methods and technologies for carbon-emission reduction in urban regeneration"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 194	66.70	2021.5
2	USA	149	8.32	2021.3
3	UK	100	5.59	2021.5
4	Australia	75	4.19	2021.3
5	Italy	59	3.30	2021.1
6	Spain	43	2.40	2021.3
7	Singapore	37	2.07	2021.2
8	Germany	36	2.01	2021.2
9	Japan	33	1.84	2021.3
10	Malaysia	32	1.79	2021.6

Table 1.2.8 Institutions with the greatest output of citing papers on "methods and technologies for carbon-emission reduction in urban regeneration"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	126	23.25	2021.0
2	China University of Mining & Technology	62	11.44	2021.8
3	Chongqing University	60	11.07	2021.5
4	Wuhan University	54	9.96	2021.1
5	Tsinghua University	41	7.56	2021.2
6	China University of Geosciences	37	6.83	2021.2
7	Tianjin University	35	6.46	2021.5
8	Beijing Normal University	33	6.09	2020.8
9	Shandong University	33	6.09	2021.2
10	Shanghai Jiao Tong University	32	5.90	2020.9

1.2.3 Spatio-temporal distribution and intelligent evaluation of giant geological disaster chains

Giant geological disaster chains often occur in high-altitude frigid mountainous areas worldwide. With the increase of construction scale, major engineering constructions around the world gradually expand to those regions with harsh geological conditions. However, complex terrain and geomorphic conditions, dense regional fault zones, and frequent strong earthquake activities pose significant disaster risks to engineering construction and safe operation. In addition, as "amplifiers" of global warming, high-altitude frigid mountainous areas have been affected by frequent extreme climate events worldwide in recent years, accelerating the occurrence of giant geological disaster chains, posing huge challenges to major engineering construction, operation, and management. Studying the spatio-temporal distribution and intelligent evaluation of giant geological disaster chains is of great significance for ensuring safe production and accelerating infrastructure construction.

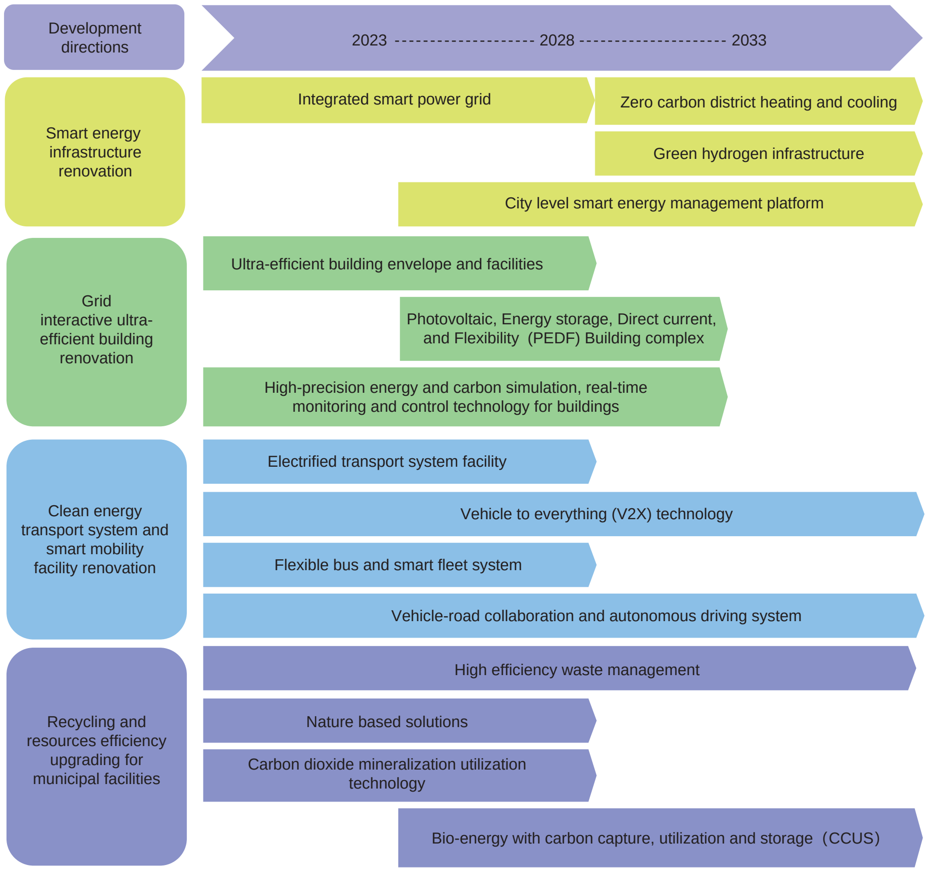

Figure 1.2.6 Roadmap of the engineering research front of “methods and technologies for carbon-emission reduction in urban regeneration”

Currently, the major topics of this research front include:

1) The spatio-temporal distribution characteristics and intelligent identification of geological disaster chains in complex disaster-prone environments. The geological disaster chain often occurs in high-altitude remote mountainous areas. The following issues are of interest: ① combining multi-source heterogeneous data interpretation algorithms based on the comprehensive remote sensing technology of multiple sources such as satellite, aerial, ground, and underground; ② establishing a database of geological disaster chains in mountainous areas to reveal the relationship between the formation of geological disasters and complex disaster gestation factors; ③ identifying the main disaster causing factors and summarizing the spatio-temporal development and distribution patterns of geological disaster chains; ④ establishing early identification markers for different types of geological disaster chains by machine learning image recognition technology; and ⑤ realizing intelligent identification of key sections of potential mutual transformation in the geological disaster chain.

2) The construction of a dynamic model for the genetic and chain evolution mechanism of geological disasters. Efforts are devoted to: ① the effects of complex disaster gestation conditions such as seismic motion, rainfall, and temperature on the mechanical properties of disaster bodies such as pore water pressure, stress, and strength; ② coupled studies from the perspectives of macroscopic geological dynamic processes and microscopic particle mechanical characteristics to reveal the critical mechanical conditions for the transformation of multiphase (solid-liquid) and multistage (flow-blockage-collapse) disasters; and ③ establishing a multi-scale coupled dynamic model that considers the macro and micro interconnected effects.

3) Establishment of resilience and risk assessment and preventive structure optimization methods for geological disaster chains. The aims are to: ① construct a random evaluation method for the disaster range to address the suddenness, uncertainty, and

complex attributes of the giant geological disaster chain; ② conduct large-scale spatio-temporal risk prediction and risk zoning evaluation combined with artificial intelligence algorithms; ③ use a Pareto optimality method to achieve local optimization and adjustment of high-risk section lines; ④ evaluate the impact resistance performance of different types of protective structures with stochastic dynamic equations and obtain the stochastic dynamic response laws of engineering structural performance indicators; and ⑤ characterize the failure probability and vulnerability of engineering structures from the probability density function level and carry out structural design based on the concept of recoverability.

4) Real time monitoring and warning, intelligent evaluation, and response to preventive decisions for large-scale giant geological disaster chains. The aftermath of geological disaster chains often involves large-scale hazards across administrative regions (national boundaries, provincial boundaries, county boundaries), resulting in delay in disaster assessment and difficulty in intelligent coordination of risk management. The requirement, therefore, is to: ① upgrade the risk assessment parameters of intelligent algorithms based on multi-source monitoring data and dynamic numerical simulation results; ② build an intelligent dynamic evaluation system and a standardized early warning system for the entire processes of geological disaster chains, including early identification, investigation and evaluation, monitoring and warning, and risk zoning; and ③ make different resilient risk prevention and control measures for different warning levels.

As shown in Table 1.1.1, 109 core papers concerning "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains" were published between 2017 and 2022, with each paper being cited 55.79 times on average. The top five countries in terms of output of core papers on this topic are China, Australia, the USA, Italy, and the UK (Table 1.2.9). China is one of the most active countries, having published 77.06% of the core papers. The five countries with the highest citations per paper were Norway, India, Vietnam, Iran, and Australia. The papers published by Chinese authors were cited 56.32 times on average, which is above the overall average. As illustrated by the international collaborative network depicted in Figure 1.2.7, close cooperation was observed among the ten most productive countries.

The five institutions that published the most core papers were China University of Geosciences, Chengdu University of Technology, Nanchang University, Chinese Academy of Sciences, and Newcastle University (Table 1.2.10). China University of Geosciences has focused on landslide displacement prediction based on multi-source data fusion and artificial intelligence algorithms, Chengdu University of Technology and Nanchang University have focused on the landslide susceptibility prediction based on machine learning algorithms. As illustrated in Figure 1.2.8, the ten most productive institutions have conducted collaborative studies in this regard.

As shown in Table 1.2.11, the five most active countries in terms of paper citations were China, the USA, Italy, Iran, and India. The top five institutions in terms of citations of core papers were China University of Geosciences, Chinese Academy of Sciences, Chengdu University of Technology, Chang'an University, and Duy Tan University (Table 1.2.12). China ranked first in the quantity of core papers produced and the number of citations of core papers, indicating that Chinese researchers pay close attention to this front.

Based on the statistical data above, research on "spatio-temporal distribution and intelligent evaluation of giant geological disaster chains" is still in its infancy. Compared with foreign peers, Chinese scholars are in a leading position.

In the next decade, the frontier in this field must lie in the following areas: spatio-temporal development characteristics and early identification of geological disaster chains based on multi-source heterogeneous data analysis; the clarification of the genetic mechanism and chain evolution mechanism under multiple disaster factors; the establishment of resilient and risk assessment and preventive optimization methods for geological hazard chains under extreme climate change; and the promotion of real-time monitoring, warning, and intelligent disaster prevention decision-making system development. At the same time, this front will gradually develop towards quantification, intelligence, and systematization. With increasingly harsh geological environments and frequent extreme weather conditions encountered during engineering construction and operation, this cutting-edge research achievement will be widely applied in engineering construction and safe operation, with huge development potential (Figure 1.2.9).

Table 1.2.9 Countries with the greatest output of core papers on “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	84	77.06	4 731	56.32	2019.7
2	Australia	14	12.84	1 124	80.29	2019.2
3	USA	14	12.84	984	70.29	2019.6
4	Italy	13	11.93	913	70.23	2019.5
5	UK	6	5.50	273	45.50	2018.2
6	Norway	4	3.67	631	157.75	2018.2
7	Iran	4	3.67	489	122.25	2020.2
8	India	3	2.75	465	155.00	2019.7
9	Vietnam	3	2.75	458	152.67	2020.0
10	France	3	2.75	135	45.00	2019.7

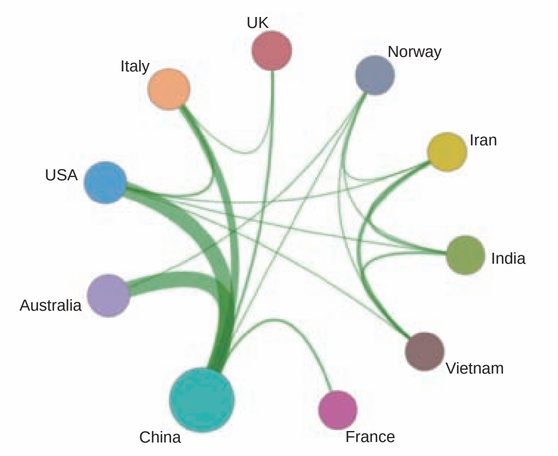

Figure 1.2.7 Collaboration network among major countries in the engineering research front of “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains”

Table 1.2.10 Institutions with the greatest output of core papers on “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China University of Geosciences	23	21.10	1 901	82.65	2019.3
2	Chengdu University of Technology	15	13.76	819	54.60	2020.0
3	Nanchang University	12	11.01	941	78.42	2019.7
4	Chinese Academy of Sciences	12	11.01	548	45.67	2019.9
5	Newcastle University	11	10.09	996	90.55	2019.4
6	Tsinghua University	9	8.26	295	32.78	2020.7
7	Sichuan University	5	4.59	293	58.60	2020.0
8	Tongji University	5	4.59	201	40.20	2020.8
9	Chang’an University	5	4.59	92	18.40	2021.2
10	The Hong Kong University of Science and Technology	4	3.67	155	38.75	2020.5

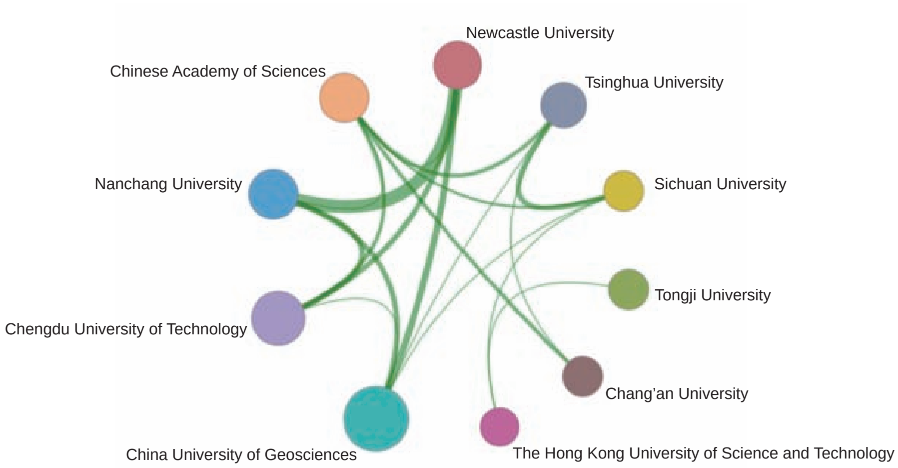

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains”

Table 1.2.11 Countries with the greatest output of citing papers on “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	2 588	54.11	2021.2
2	USA	358	7.48	2020.8
3	Italy	306	6.40	2020.9
4	Iran	284	5.94	2020.7
5	India	276	5.77	2021.3
6	UK	232	4.85	2020.9
7	Vietnam	198	4.14	2020.5
8	Australia	175	3.66	2020.8
9	Germany	135	2.82	2020.8
10	Canada	117	2.45	2020.8

Table 1.2.12 Institutions with the greatest output of citing papers on “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	China University of Geosciences	369	20.79	2020.9
2	Chinese Academy of Sciences	350	19.72	2021.1
3	Chengdu University of Technology	253	14.25	2021.2
4	Chang’an University	129	7.27	2021.2
5	Duy Tan University	108	6.08	2020.1
6	Tongji University	104	5.86	2021.2
7	Southwest Jiaotong University	103	5.80	2021.4
8	Sichuan University	94	5.30	2021.3
9	Chongqing University	94	5.30	2021.3
10	Wuhan University	89	5.01	2021.1

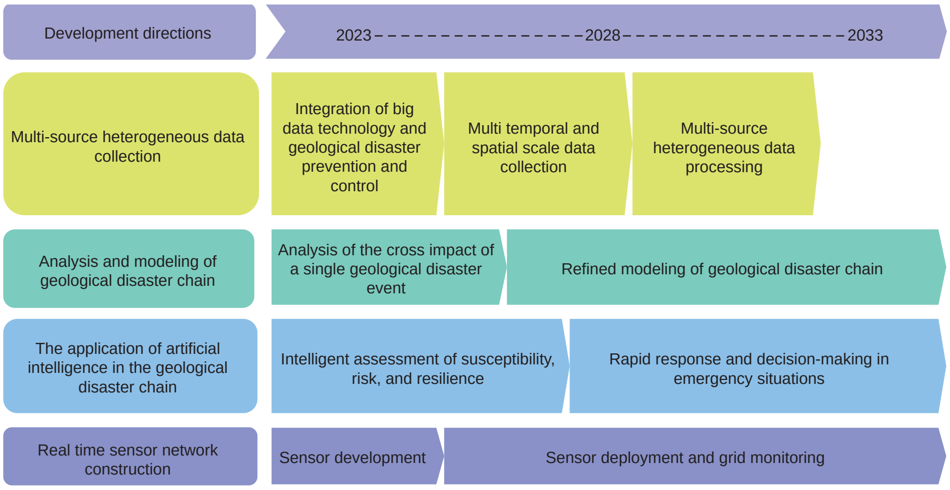

Figure 1.2.9 Roadmap of the engineering research front of “spatio-temporal distribution and intelligent evaluation of giant geological disaster chains”

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

The Top 10 engineering development fronts in the fields of civil, hydraulic, and architectural engineering are summarized in Table 2.1.1. These fronts cover a variety of disciplines, including municipal engineering, surveying and mapping engineering, urban planning and landscaping, architectural design and theory, transportation engineering, hydraulic engineering, construction materials, geotechnical and underground engineering, and structural engineering. The panel experts nominated the following development fronts: “intelligent detection and rehabilitation technology of drainage pipe leakage”, “core technology for 1 mm level global and regional coordinate frame”, and “advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments”. The remaining development fronts were identified from patent maps and agreed in the expert panel meetings. Table 2.1.2 presents annual statistics on patents registered between 2017 and 2022 related to these Top 10 development fronts.

(1) Intelligent detection and rehabilitation technology of drainage pipe leakage

Drainage pipe leakage has become one of the main bottlenecks restricting the safe discharge of stormwater and complete collection and treatment of wastewater. Intelligent detection and rehabilitation technology is designed to detect, diagnose and evaluate the level of structural defects in drainage pipe, and carry out low disturbance, high quality and proactive repair, which makes the drainage pipe run safely and efficiently. Moreover, along with the development of the Internet of Things, big data and cloud computing, the leakage detection technology will shift from periodic passive detection to proactive monitoring, providing support for preventive response to potential problems in drainage pipes. The main research areas include: ① digital base technology, including a domestic geographical information system and accurate measurement under complex medium conditions; ② intelligent detection technology, including identification of hidden risks and structural health monitoring via electromagnetic and sound waves; ③ smart assessment technology, including health prediction and adaptive modeling driving by data and models; and ④ efficient early-response technology suitable for large and extra-large drainage pipes, including availability of materials suitable for long distance transportation, corrosion environment and demanding mechanical conditions. The main development trend in the future mainly focuses on precise quantitative detection technology, high strength and high adaptability early-response technology, and detection and rehabilitation quality process control technology based on mobile Internet

Table 2.1.1 Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Intelligent detection and rehabilitation technology of drainage pipe leakage	22	43	1.95	2020.8
2	Core technology for 1 mm level global and regional coordinate frame	55	95	1.73	2020.3
3	Digital technology for the protection and utilization of urban historical and cultural resources	19	122	6.42	2020.0
4	Generation technique for space programming of large public buildings supported by artificial intelligence	21	27	1.29	2021.1
5	Advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments	19	42	2.21	2020.4
6	*In-situ* observation technologies and equipment in complicated and extreme underwater environments	47	234	4.98	2019.8
7	The technology of preparing carbon-negative building materials from multi-source industrial byproducts	106	985	9.29	2019.5
8	Fast and accurate drilling and sensing technology in complex geological environment	258	1 257	4.87	2019.3
9	Prefabricated structures with components and modular units	286	1 694	5.92	2019.3
10	Smart irrigation and drainage technology and equipment for high productivity farmland	185	1 679	9.08	2019.4

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in civil, hydraulic, and architectural engineering

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Intelligent detection and rehabilitation technology of drainage pipe leakage	1	0	1	6	7	7
2	Core technology for 1 mm level global and regional coordinate frame	6	2	6	16	8	17
3	Digital technology for the protection and utilization of urban historical and cultural resources	3	1	3	4	2	6
4	Generation technique for space programming of large public buildings supported by artificial intelligence	1	0	4	0	3	13
5	Advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments	3	1	1	3	3	8
6	*In-situ* observation technologies and equipment in complicated and extreme underwater environments	7	8	3	8	10	11
7	The technology of preparing carbon-negative building materials from multi-source industrial byproducts	15	19	23	16	17	16
8	Fast and accurate drilling and sensing technology in complex geological environment	47	42	53	51	42	23
9	Prefabricated structures with components and modular units	37	57	52	72	65	3
10	Smart irrigation and drainage technology and equipment for high productivity farmland	35	28	33	36	27	26

technology. Between 2017 and 2022, 22 patents relevant to this research front were registered. These patents received 43 citations, with an average of 1.95 citations per patent.

(2) Core technology for 1 mm level global and regional coordinate frame

A coordinate framework is a foundation for describing changes of the Earth, including in terms of shape, expressing geospatial information. It is also a key geospatial information infrastructure for expanding human activities and promoting social development. At present, the latest international Earth reference framework cannot meet the needs of large-scale or global millimeter level Earth system dynamic change monitoring, so the core technology for millimeter level coordinate frameworks has become the forefront in this field. Development trends in this research front include the following. ① Precision spatial geodetic data processing technology determines the optimal VLBI/SLR/GNSS/DORIS data processing strategy through refined mathematical models. Based on this, global benchmark station data is uniformly reprocessed to eliminate or weaken the impact of technical system errors, providing more accurate input data for the establishment of millimeter level coordinate frameworks. ② Modeling the nonlinear motion of the reference station, aiming at the nonlinear displacement caused by geophysical effects, integrating environmental loads, thermal expansion, and other models to establish millimeter level reference station geophysical motion modeling, providing support for the establishment of a millimeter level coordinate framework. ③ A combination of spatial geodetic techniques, such as VLBI, SLR, GNSS, DORIS, etc., providing progress towards establishing a global coordinate framework; ④ Modeling of geocentric motion, combining multiple spatial geodetic techniques and geophysical models to invert geocentric motion, solves the inconsistency between the definition and implementation of the coordinate frame origin, and provides a more accurate geocentric reference framework for geodynamic research. The future development of this front involves precision spatial geodetic data processing technology, nonlinear motion modeling of reference stations, and combination of spatial geodetic technologyand geocentric motion modeling. Between 2017 and 2022, 55 patents relevant to this research front were registered. These patents received 95 citations, with an average of 1.73 citations per patent.

(3) Digital technology for the protection and utilization of urban historical and cultural resources

Protection and utilization of urban historical and cultural resources is an important topic of global concern, involving many fields such as urban cultural heritage, a mixture of natural and cultural heritage, and cultural landscapes. China's urban historical and cultural resources are exceptionally rich, but there are still problems in the field of resource protection and utilization, such as lagging behind others in theoretical research, insufficient systematicity and completeness of basic data, and limited scope of application of new technological methods. Along with the development of a new round of digital technology, the latest intelligent digital technology is being introduced globally into the traditional field of historical and cultural resources protection and utilization, which improves the systematization of the resource protection work and expands the breadth and depth of historical and cultural resources utilization. Thus, strengthening the development and application of the digital technology system for the protection and utilization of urban historical and cultural resources engineering development in China is of great significance for enhancing cultural self-confidence and building a strong cultural country. The forefront of research and development is primarily reflected in the following aspects: ① database construction technology for urban historical and cultural resources; ② intelligent protection technology for urban historical and cultural resources; ③ digitally empowered utilization technology for urban historical and cultural resources; and ④ integrated technology for preservation and utilization of urban historical and cultural resources. The key development directions focus on multiple data source integration, risk perception monitoring, assessment and projection, spatial planning response, value dissemination and utilization, and planning technology integration. Between 2017 and 2022, 19 patents relevant to this research front were registered. These patents received 122 citations, with an average of 6.42 citations per patent.

(4) Generation technique for space programming of large public buildings supported by artificial intelligence

Facing the urgent need to strengthen the whole-process control of large and complex construction projects, the generation technique of architectural space programming integrates multi-disciplinary and whole-process data in architectural design with the utilization of frontier development of artificial intelligence. The technique is able to make complex decisions in architectural space programming, achieving a closed-loop of data interchange from precise diagnosis, through intelligent programming, to integral design. Thus it improves the quantitative nature of decision-making in architectural design and will contribute to solving related problems, such as provision of intelligent decision-making tools for complex architectural programming, acquisition and correlation of spatial performance and human perception data, conversion and connection mechanisms for lifecycle design data, and internal mapping mechanisms between architectural programming and post-occupancy evaluation. The main technical directions include: ① uncertain and fuzzy complex decision-making technique based on graph topology; ② coupling technique of objective evaluation of spatial environment and multi-dimensional ubiquitous human perception information; ③ intelligent integral design technique throughout the building lifecycle; and ④ application of feed-forward inference technique of post-occupancy evaluation data. The major development directions of this study are as follows. Firstly, the scope of application of the technique will be expanded from architecture to full-scale urban space, shifting the focus from the form of spatial composition to places and spatial networks with an emphasis on the correlation of elements within the system. Secondly, the technique will evolve from being data-oriented to being data-driven, strengthening dynamism and connectivity of data, thereby providing powerful data support for achieving intelligent architectural space programming. Thirdly, while the aim is developing from assisting low-dimensional decision-making to solving complex high-dimensional problems, the technique will carry out intelligent technology integration demonstration applications for architectural programming and post occupancy evaluation of large construction projects with intelligence as the main path. Between 2017 and 2022, 21 patents relevant to this research front were registered. These patents received 27 citations, with an average of 1.29 citations per patent.

(5) Advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments

The objective of advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments is to address challenges posed by extreme weather conditions, geological factors, and natural disasters. These technologies employ advanced maintenance and upkeep techniques to ensure that infrastructure, such as roads, railway tracks, and airports, maintains outstanding construction quality, efficient operational performance, and long-term durability under extreme conditions. This field focuses on ensuring the reliability and stability of transportation systems under adverse environmental conditions, such as high temperatures, heavy rainfall, severe freezing and thawing, chloride salt erosion, while also addressing natural disasters like typhoons, earthquakes, and heavy rainfall to ensure safety. Key technical directions include: ① adaptation of materials and structural design for extreme environments, and development of new materials and structural designs to ensure stability and durability of road, rail, and airport facilities under extreme climate and geological conditions; ② intelligent monitoring and maintenance, with utilization of sensor technologies, monitoring systems, and other tools for real-time monitoring of the status of engineering facilities during construction and operation phases, and with early detection of anomalies to ensure high-quality construction and safe and stable operation of the facilities; ③ disaster resilience assessment and early warning, including use of data analysis and simulation techniques to assess and predict the risks of natural disasters in extreme environments, providing a scientific basis for prevention and response; and ④ emergency response and recovery, with development of emergency response plans and establishment of rapid recovery mechanisms to ensure timely repair and recovery work in the event of disasters. In the future, advanced technologies for the construction and maintenance of road, rail, and airport infrastructure in extreme environments will evolve in the following directions: 1) green and sustainable development; 2) digitalization and intelligent applications; 3) adoption of new materials and techniques; and 4) enhancement of structural resilience. Between 2017 and 2022, 19 patents relevant to this research front were registered. These patents received 42 citations, with an average of 2.21 citations per patent.

(6) *In-situ* observation technologies and equipment in complicated and extreme underwater environments

Underwater on-situ observation involves collection, analysis and display of dynamic change data such as submarine sediment, submarine geological environment and the benthic boundary layer, etc. Such data can be widely used in marine disaster warning, marine resource development and utilization, as well as marine ecological environment protection, governance and restoration, etc. Complicated and extreme marine environments, with features that may include underwater geological conditions, underwater currents, storm surges, and tsunamis, not only cause significant changes in the submarine sediment, submarine geological environment and benthic boundary layer, but also have an impact on the safety of the underwater *in-situ* observation system, on the accuracy of observation data and on the stability of information transmission. The main issues that need to be studied and solved regarding *in-situ* observation technologies and equipment in complicated and extreme underwater environment include the following: ① development of high-precision, high stability and long lifespan independent observation instruments suitable for various observation purposes in complicated and extreme underwater environments; ② development of safe and reliable autonomous mobile observation platforms suitable for complicated and extreme underwater environments, to expand the spatial scale of observations; ③ development of wide area real-time information transmission and precise time synchronization information transmission system, and building large-scale spatio-temporal scale intelligent control underwater *in-situ* observation networks; and ④ development of high energy density, long lifespan and high safety energy storage systems, to provide reliable energy and power support for systematic, collaborative and intelligent underwater *in-situ* observations. Between 2017 and 2022, 47 patents relevant to this research front were registered. These patents received 234 citations, with an average of 4.98 citations per patent.

(7) The technology of preparing carbon-negative building materials from multi-source industrial byproducts

The technology of preparing carbon-negative building materials from multi-source industrial byproducts involves preparation of carbon-negative building materials by the carbonation reaction of alkaline earth metals, e.g., Ca^{2+} and Mg^{2+}, contained in industrial byproducts. The property of the materials prepared and the energy consumed via processing can be further optimized by introducing multiple byproducts and their physical and chemical effects. This technology contributes to carbon emission mitigation in the construction sector and facilitates the recycling of waste materials. The most investigated topics in this field include: ① the carbonation reactivity of calcium (alumino-) silicate materials and approaches to enhancing the reactivity; ② the carbonation reaction, crystallography of carbonation products, and microstructural changes induced by the reaction; ③ approaches to enhancing CO_2 transportation and the carbonation reaction; and ④ industrial processing and facilities. The application of this technology relies on a balance between the materials engineering and environmental performances. For future research, breakthroughs can be made on: ① high-performance cementitious systems with multi-source byproducts; ② multiple reaction mechanisms coupling carbonation and hydration; ③ characterization of the reaction-transport processes by 3D and in-situ test methods; ④ coupling materials preparation with other industrial processes; and ⑤ standards on materials performance and the assessment of environmental impacts. Between 2017 and 2022, 106 patents relevant to this research front were registered. These patents received 985 citations, with an average of 9.29 citations per patent.

(8) Fast and accurate drilling and sensing technology in complex geological environments

"Fast and accurate drilling and sensing technology" refers to the use of advanced drilling technology and equipment to rapidly obtain underground physical data and characterize geological conditions in the face of extremely complex geological conditions during deep underground exploration and engineering construction. Through technologies such as transmission, control, information perception, and data fusion, this approach enables the perception of equipment status and geological environment, precise determination of various parameters, reliable execution of instructions, and the development of intelligent detection equipment, standardized drilling processes, controllable borehole quality, advanced accident prediction, intelligent control of process parameters, and self-assessment of geological parameters. These enhancements ultimately increase the efficiency of obtaining underground physical data and geological information in drilling projects. In deep and complex geological environments, challenges include high temperatures, high pressures, long implementation periods, and significant protocol parameters. These challenges lead to issues in drilling projects such as inadequate drilling equipment power, reduced service life of downhole tools, difficulties in controlling borehole trajectories, and the susceptibility of well-logging instruments to high-temperature failures. The primary technological directions for fast and accurate drilling and sensing technology in complex deep geological environments include: ① development of deep and intelligent automated drilling systems and drilling tools; ② multi-process efficient and high-speed drilling techniques; ③ efficient core sampling technology for complex deep formations; ④ horizontal directional drilling and in-hole comprehensive testing techniques; ⑤ in-well data measurement, transmission, intelligent drilling control based on advanced sensors; ⑥ enhancement of reliability for tools and instruments in high-temperature hard rock formations; and ⑦ advanced ahead-of-time perception technology regarding the downhole formation environment and drilling equipment status. The future development trend is towards lightweight, end-to-end, and automated drilling technology equipment upgrades, as well as the construction of advanced intelligent sensing, measurement, transmission, control, and closed-loop drilling technologies, integrating multiple sources of information from the underground environment. Between 2017 and 2022, 258 patents relevant to this research front were registered. These patents received 1 257 citations, with an average of 4.87 citations per patent.

(9) Prefabricated structures with components and modular units

Construction industrialization has an inevitable tendency by which the traditional construction industry follows the modern industrial mode of production with a purpose of improving construction efficiency, saving energy, reducing consumption, and achieving high quality development. The main characteristics may include standardized design, factory production, assembly construction, integrated decoration and information management, etc. As an efficient way to realize construction industrialization, prefabricated buildings can be assembled on-site with standardized components prefabricated by factory production lines. Therefore, it is of utmost importance for construction industrialization to research and develop effective prefabricated building structural systems, as well as corresponding building components and construction technologies. Current research focuses on: ① prefabricated building structure systems and corresponding design methods; ② prefabricated building components and modular units (including connection components) with different degrees of integration and corresponding design methods; ③ prefabricating technology for factory production of building components and assembling technology for buildings on-site; ④ integrated construction technology; and ⑤ digital and intelligent construction technology. For the ongoing research trend, prefabricated building structure systems will be developed directly from effective components with high-efficiency and high-performance instead of reasonable decomposition of traditional RC, steel or timber structure systems, i.e. using the forward design method. New research fields on intelligent disaster prevention, structural toughness improvement according to prefabricating and assembling construction logistic will develop. The building components will facilitate a high degree of integration, taking forms such as 2D panels or 3D modular units, and standardization and serialization will be emphasized to satisfy the diversity of buildings. Integrating all professionals and the whole industry is focused rather than a single integration, such as structural members with decoration, structural members with specific functions, buildings and equipment. Furthermore, product thinking for buildings and the digital twinning technology will offer wide technical support for construction industrialization and intelligentization. Between 2017 and 2022, 286 patents relevant to this research front were registered. These patents received 1 694 citations, with an average of 5.92 citations per patent.

(10) Smart irrigation and drainage technology and equipment for high productivity farmland

Smart irrigation and drainage technology and equipment refers to the integrated use of technologies such as the internet of things (IoTs), advanced sensors, remote sensing, edge computing, cloud computing, and artificial intelligence (AI) in modern agricultural production. It involves multi-dimensional perception and intelligent analysis of crop growth conditions, field water conditions, irrigation and drainage channel (pipeline) status, and environmental factors. Through intelligent equipment, the smart technology enables precise monitoring and control of the irrigation and drainage processes, coordinating field water conditions, enhancing resilience to flooding and drought disasters, meeting crop growth demands, reducing labor costs, improving management efficiency, and achieving high yields and efficiency. The main research aspects of smart irrigation and drainage technology and equipment include: ① precise diagnosis of crop water and nutrient status in irrigated farmlands, as well as intelligent decision-making technologies for efficient irrigation and drainage with enhanced water and nutrient use efficiency and reduced pollutants discharge; ② development of easy-assembly and easy-operation irrigation and drainage systems with multi-level high-performance measurement and control terminals; ③ irrigation and drainage digital twin systems with self-learning capabilities and strong timeliness; and ④ intelligent optimization technology and collaborative regulation mode for all-season distributed control of irrigation and drainage system, aiming at improving the productivity of farmland. The development trends of smart irrigation and drainage technology and equipment are as follows: ① breaking through the limitations of sensor technology by introducing diverse sensing methods to achieve the fusion analysis of multi-source and multi-modal data, providing more precise and comprehensive information for high productivity farmland systems; ② enhancing the scientific and operational performances of field decisions through the fusion and interaction of data, models, and knowledge; ③ strengthening the autonomous decision-making capabilities of irrigation and drainage equipment and systems, increasing the cloud-edge computing capability and collaborative interconnection capability of equipment, and improving overall precision and efficiency through data sharing and collaboration; and ④ innovative methods, new technologies, new equipment, and new models for irrigation and drainage, realizing unmanned, intelligent, lightweight, and end-to-end irrigation and drainage for high productivity farmland. Between 2017 and 2022, 185 patents relevant to this research front were registered. These patents received 1 679 citations, with an average of 9.08 citations per patent.

2.2 Interpretations for three key engineering development fronts

2.2.1 Intelligent detection and rehabilitation technology of drainage pipe leakage

Drainage pipe leakage weakens the capacity of stormwater drainage and efficiency of wastewater treatment. It has become one of the main bottlenecks restricting the safe discharge of stormwater and complete collection and treatment of wastewater, and it induces environmental problems and safety risks of soil-underground water pollution, wastewater overflow, and road collapse. Intelligent detection and rehabilitation technology is designed to detect, diagnose and evaluate the level of structural defects in drainage pipe, and carry out low disturbance, high quality and proactive rehabilitation.

Due to the invisibility, widespread distribution, huge quantity, complex flow regime, and poor internal conditions of drainage pipes, the traditional detection technologies represent drawbacks of limited applicability, incomplete data results, and delayed prediction. In addition, the repair technologies are limited to reducing water level, excavation, and standardization. Moreover, along with the development of Internet of Things, big data and cloud computing, the leakage detection technology will shift from passive and periodic detection to proactive monitoring, providing support for proactive rehabilitation of drainage pipes.

Frontier scientific issues of intelligent detection and rehabilitation technology of drainage pipe leakage are as follows:

1) Digital base technology, including domestic geographical information system and accurate measurement of flow rate and water quality under complex medium conditions.

2) Intelligent detection technology, which includes: ① pipe external inspection technology basing on geological radar, concrete thickness detection, and rebar distribution detection; ② pipe identification technology of hidden risks via electromagnetic and sound waves; and ③ structural health monitoring technology for large-diameter and long-distance pipes.

3) Smart assessment technology, which includes: ① application of an evolutionary algorithm of pipeline services synergistically driven by data and modeling; ② failure prediction of drainage pipes influenced by multidimensional drive and multi-source data; and ③ rapid adaptive modeling of drainage pipeline networks based on the online monitoring data for crucial nodes.

4) Efficient rehabilitation technology, which includes: ① rehabilitation materials adapted to long-distance transportation, corrosive environments, and variable mechanical conditions, such as die casting pipe rehabilitation technology by using high strength and quick drying grouting materials; and ② repair technology suitable for large and extra-large pipes, such as structural strength enhancement via modular lining.

As listed in Table 2.1.1, 22 patents related to this topic were registered between 2017 and 2022, with each patent being cited 1.95 times on average. The country that registered the most patents was China (Table 2.2.1). China was at the forefront of development, contributing 100% of the patents. The citations per paper of Chinese patents was 1.95.

The five institutions that produced the most patents were Zhengzhou University, Zhengzhou Anyuan Engineering Technology

Company Limited, Hohai University, Nanjing Hohpower Information Technology Company Limited, and Guangzhou Yuntong Water Company Limited (Table 2.2.2). Cooperation among these institutions is rare (Figure 2.2.1).

The crucial development front of "intelligent detection and rehabilitation technology of drainage pipe leakage" in the coming five to ten years will focus on precise quantitative detection technology, high strength and high adaptability rehabilitation technology, and detection and rehabilitation quality process control technology based on mobile Internet technology. Precise quantitative detection technology mainly includes panoramic/laser quantitative detection technology, optical fiber leakage detection technology based on temperature and pressure, pipe residual strength detection technology based on mechanical elastic waves, pipe residual wall thickness detection technology based on ultrasonic thickness measurement, infrared camera detection method, magnetic flux leakage method, transient electromagnetic method, and pipe deformation detection technology involving calipers, laser instruments, or multi-sensors. High strength and high adaptability rehabilitation technology mainly focuses on breakthroughs in new materials, new technologies, new crafts, new equipment. Breakthroughs can not only broaden the application scenarios and quality of repair technology but also fulfill the repair needs of drainage pipes in corrosive, confined, and wet conditions. Application of mobile Internet technology for the management of detection and repair of construction enhances management effectiveness, ensures the quality of the construction process, and verifies the authenticity of the data (Figure 2.2.2).

Table 2.2.1 Countries with the greatest output of core patents on "intelligent detection and rehabilitation technology of drainage pipe leakage"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	22	100.00	43	100.00	1.95

Table 2.2.2 Institutions with the greatest output of core patents on the "intelligent detection and rehabilitation technology of drainage pipe leakage"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Zhengzhou University	3	13.64	8	18.60	2.67
2	Zhengzhou Anyuan Engineering Technology Company Limited	2	9.09	8	18.60	4.00
3	Hohai University	1	4.55	9	20.93	9.00
4	Nanjing Hohpower Information Technology Company Limited	1	4.55	9	20.93	9.00
5	Guangzhou Yuntong Water Company Limited	1	4.55	5	11.63	5.00
6	Shenzhen Qianhai Yuntong Water Company Limited	1	4.55	5	11.63	5.00
7	Henan Aibit Technology Company Limited	1	4.55	4	9.30	4.00
8	Guangzhou Lixin Electronic Technology Company Limited	1	4.55	3	6.98	3.00
9	Huazhong University of Science and Technology	1	4.55	1	2.33	1.00
10	Qingyuan Construction Safety Inspection Company Limited	1	4.55	1	2.33	1.00

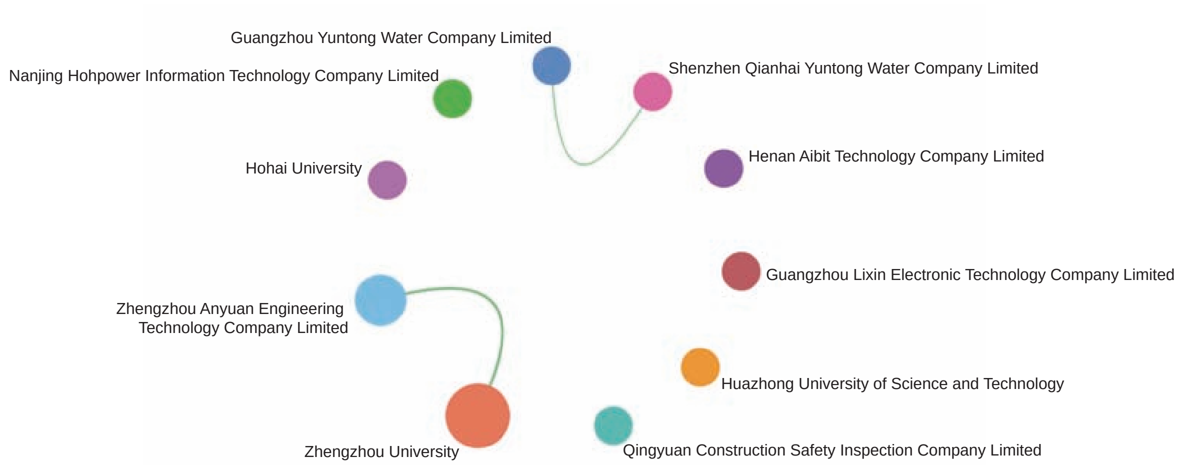

Figure 2.2.1 Collaboration network among major institutions in the engineering development front of "intelligent detection and rehabilitation technology of drainage pipe leakage"

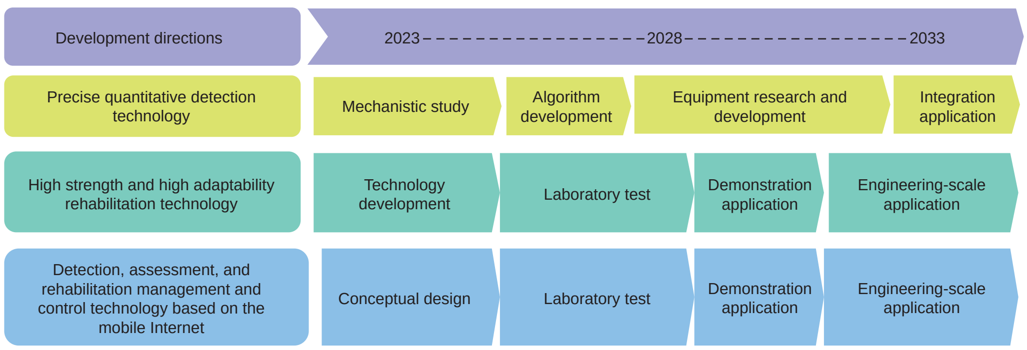

Figure 2.2.2 Roadmap of the engineering development front of "intelligent detection and rehabilitation technology of drainage pipe leakage"

2.2.2 Core technology for 1 mm level global and regional coordinate frame

The coordinate framework is a foundation for describing the shape of the Earth and changes to that, and is also a key geospatial information infrastructure for expanding human activities and promoting social development. It can provide not only basic data for deep space exploration, urban construction, disaster relief and disaster reduction, but also a unified high-precision spatial benchmark for global change detection and scientific research, such as geodynamic inversion, and earthquake, climate, and hydrological monitoring. It is a key geospatial information infrastructure for expanding human activities and promoting social development.

The existing international Earth reference framework does not meet the needs of monitoring the dynamic changes of large-scale or global millimeter scale Earth systems. Development of the core technology for a millimeter level coordinate framework has become a disciplinary goal and important challenge for the international geodetic community in the 21st century. Development trends in this research front include the following.

1) Precision spatial geodetic data processing technology to determine the optimal applications of Very-Long-Baseline Interferometry (VLBI)/Satellite Laser Ranging (SLR)/Global Navigation Satellite System (GNSS)/Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) data processing strategy, through refined mathematical models. Based on this, global benchmark station data can be uniformly reprocessed to eliminate or weaken the impact of technical system errors, providing sufficiently precise input data for the establishment of millimeter level coordinate frameworks.

2) Modeling the nonlinear motion of the reference station, targeting the nonlinear displacement caused by geophysical effects,

integrating environmental loads, thermal expansion.

3) A combination of spatial geodetic techniques, utilizing spatial geodetic techniques such as VLBI, SLR, GNSS, DORIS, etc.

4) Modeling of geocentric motion, combining multiple spatial geodetic techniques and geophysical models to invert geocentric motion, solving the inconsistency between the definition and implementation of the coordinate frame origin, and providing a more accurate geocentric reference framework for geodynamic research.

Research institutions that produced the most papers in this field include Wuhan University, The Chinese Academy of Surveying & Mapping, and The Institute of Geodesy and Geophysics.

As listed in Table 2.1.1, 55 patents related to this topic were registered between 2017 and 2022, with each patent being cited 1.73 times on average. The three countries that registered the most patents were China, Russia, and Republic of Korea (Table 2.2.3). Among these countries, China was at the forefront of development, contributing 83.64% of the patents. The average citation frequency of Chinese patents was 1.85.

The five institutions that produced the most patents were Xi'an Applied Optics Research Institute, a certain unit of the People's Liberation Army of China, Northwestern Polytechnical University, Qianxun Location Network Company Limited, and China Electronics Technology Group Corporation (Table 2.2.4).

The future development of this front in the coming five to ten years will involve precision spatial geodetic data processing technology, nonlinear motion modeling of reference stations, combination of spatial geodetic technology, and geocentric motion modeling (Figure 2.2.3).

Table 2.2.3 Countries with the greatest output of core patents on "core technology for 1 mm level global and regional coordinate frame"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	46	83.64	85	89.47	1.85
2	Russia	6	10.91	4	4.21	0.67
3	Republic of Korea	1	1.82	4	4.21	4.00
4	France	1	1.82	2	2.11	2.00
5	Poland	1	1.82	0	0.00	0.00

Table 2.2.4 Institutions with the greatest output of core patents on "core technology for 1 mm level global and regional coordinate frame"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Xi'an Applied Optics Research Institute	4	7.27	16	16.84	4.00
2	A certain unit of the People's Liberation Army of China	3	5.45	1	1.05	0.33
3	Northwestern Polytechnical University	2	3.64	6	6.32	3.00
4	Qianxun Location Network Company Limited	2	3.64	5	5.26	2.50
5	China Electronics Technology Group Corporation	2	3.64	4	4.21	2.00
6	Beijing Institute of Environmental Features	2	3.64	0	0.00	0.00
7	Satellite Surveying and Mapping Application Center NASG	1	1.82	12	12.63	12.00
8	Wuhan University	1	1.82	5	5.26	5.00
9	Beihang University	1	1.82	4	4.21	4.00
10	Institute of Electronics, Chinese Academy of Sciences	1	1.82	4	4.21	4.00

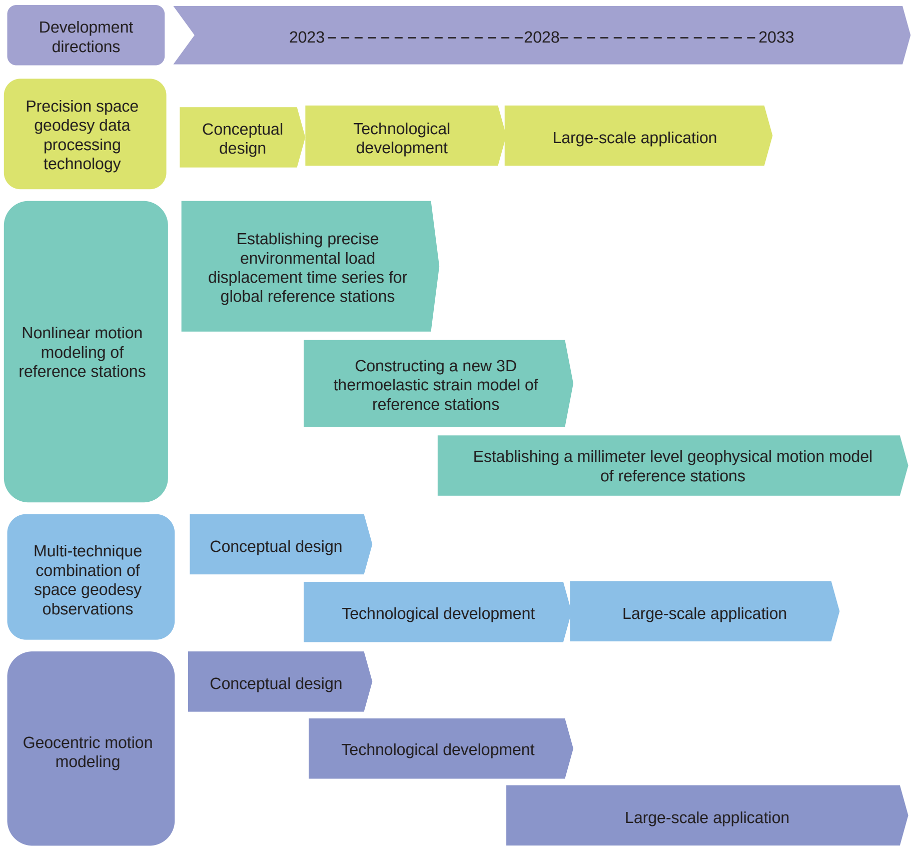

Figure 2.2.3 Roadmap of the engineering development front of "core technology for 1 mm level global and regional coordinate frame"

2.2.3 Digital technology for the protection and utilization of urban historical and cultural resources

The core of the digital technology for the preservation and utilization of urban historical and cultural resources lies in enabling a coordinated approach through digital technology. This transforms preservation from static and passive methods to dynamic and proactive strategies, fully realizing the important value that historical and cultural resources hold for urban space and societal development. The forefront of research and development is primarily reflected as follows.

1) Database construction technology for urban historical and cultural resources: Creating a digital archive of historical and cultural resources is fundamental for achieving comprehensive resource preservation. This not only supports the restoration and protection of cultural heritage but also serves as a carrier for heritage value dissemination and the need for coordinated management of various resources. However, historical and cultural resources vary in type, including tangible heritage, intangible heritage, and movable and immovable cultural artifacts. Moreover, the tangible resources vary significantly in spatial scale. Key to addressing this challenge is the development of technology for integrating diverse and heterogeneous data from multiple sources and ensuring seamless data connectivity across various scales.

2) Intelligent protection technology for urban historical and cultural resources: The safety of urban historical and cultural resources is influenced by both natural hazards (such as climate change and natural disasters) and human activities (such as resource utilization and development). Digital technology provides technical feasibility for establishing an interactive, dynamic, and intelligent proactive protection mechanism that incorporates "perception monitoring-dynamic assessment-risk warning-measure response" linkages to address various risks.

3) Digitally empowered utilization technology for urban historical and cultural resources: Digitization of urban historical and cultural resources serves not only to preserve historical information but is also a crucial means for value generation. Several

European countries have initiated digital museum projects, enhancing interactive experiences through technologies like virtual reality. They have developed applications for devices such as smartphones and have integrated urban historical and cultural resources into emerging digital industries like electronic gaming.

4) Integrated technology for preservation and utilization of urban historical and cultural resources: Through integrated technology, the three major phases of "database construction-risk assessment, response-resource utilization, and value dissemination" are interconnected, promoting mutual enhancement through the empowerment of digital technology. Additionally, preservation and utilization of urban historical and cultural resources should not remain an isolated technology. It should be integrated into the broader technical framework of land and spatial resource preservation and utilization, fostering horizontal coordination with other urban resource management efforts and vertical integration across spatial levels within the broader land and spatial context to ultimately achieve comprehensive, all-encompassing, and full-cycle land and spatial resource management.

As listed in Table 2.1.1, 19 patents related to this topic were registered between 2017 and 2022, with each patent being cited 6.42 times on average. The three countries that registered the most patents were China, Romania, and Republic of Korea (Table 2.2.5). Among these countries, China was at the forefront of development, contributing 78.95% of the patents. The average citation frequency of Chinese patents was 7.60.

The five institutions that produced the most patents were Central South University, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, China University of Geosciences (Wuhan), Dingchen Construction Management Company Limited, and Korean Advanced Institute of Science and Technology (Table 2.2.6).

Table 2.2.5 Countries with the greatest output of core patents on "digital technology for the protection and utilization of urban historical and cultural resources"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	15	78.95	114	93.44	7.60
2	Romania	3	15.79	0	0.00	0.00
3	Republic of Korea	1	5.26	8	6.56	8.00

Table 2.2.6 Institutions with the greatest output of core patents on "digital technology for the protection and utilization of urban historical and cultural resources"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Central South University	1	5.26	40	32.79	40
2	Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences	1	5.26	35	28.69	35
3	China University of Geosciences (Wuhan)	1	5.26	11	9.02	11
4	Dingchen Construction Management Company Limited	1	5.26	11	9.02	11
5	Korea Advanced Institute of Science and Technology	1	5.26	8	6.56	8
6	Chengdu University of Technology	1	5.26	6	4.92	6
7	Institute of Urban Environment, Chinese Academy of Sciences	1	5.26	4	3.28	4
8	Shenyang University of Technology	1	5.26	3	2.46	3
9	Suzhou Planning and Design Research Institute Company Limited	1	5.26	2	1.64	2
10	Xi'an Zhongke Xiguang Aerospace Technology Company Limited	1	5.26	2	1.64	2

The key development directions for the "digital technology for the protection and utilization of urban historical and cultural resources" project in the next 5–10 years will focus on multiple data source integration, risk perception monitoring, assessment and projection, spatial planning response, value dissemination and utilization, and planning technology integration (Figure 2.2.4).

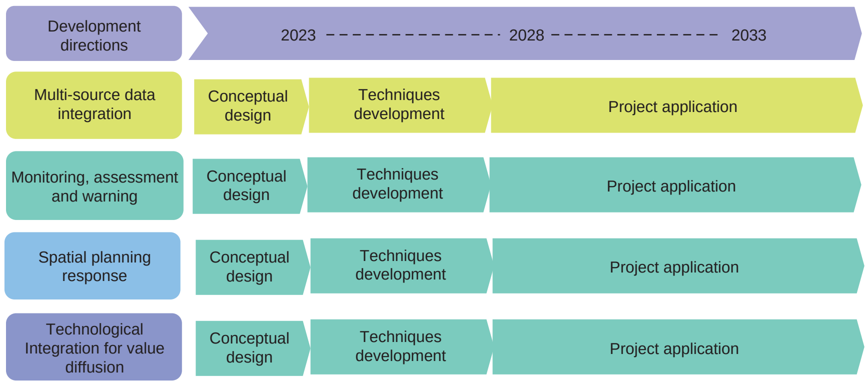

Figure 2.2.4 Roadmap of the engineering development front of "digital technology for the protection and utilization of urban historical and cultural resources"

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VI. Environmental and Light Textile Engineering

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The Top 10 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 number of core papers published annually for each research front between 2017 and 2022 are summarized in Tables 1.1.1 and 1.1.2, respectively.

(1) Environmental risks of emerging contaminants in soil

Emerging contaminants are toxic and harmful chemicals that feature biological toxicity, environmental persistence, and bioaccumulation. These contaminants pose a significant risk to both the ecological environment and human health. However, they have not been adequately addressed in current environmental management practices or regulations. Currently, emerging contaminants of concern globally include persistent organic pollutants regulated by international conventions, endocrine disruptors, antibiotics, microplastics, among others.

Emerging contaminants in soil come from a wide range of sources and varieties, and the soil matrix is complex. Therefore, the research and development of high-throughput screening technology with high sensitivity and multiple targets and the early establishment of standard methods are of great significance for determining emerging contaminants rapidly and efficiently, ensuring the accuracy of research results and completing environmental risk assessment.

Many research scholars have assessed individual emerging contaminants without considering the possibility of combined or

Table 1.1.1 Top 10 engineering research fronts in environmental and light textile engineering

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Environmental risks of emerging contaminants in soil	86	4 632	53.86	2021.1
2	Non-CO_2 greenhouse gas emission reduction and utilization	255	4 976	19.51	2020.3
3	Technologies for prevention and remediation of micro-pollution of drinking water sources and safe utilization of micro-polluted water	85	10 560	124.24	2018.6
4	Frontier interpretation of greenhouse gas emissions from aquaculture	33	1 502	45.52	2019.9
5	Neural network-based ensemble prediction method	50	5 016	100.32	2020.4
6	Research on the impact of urbanization on hourly extreme precipitation	47	743	15.81	2020.4
7	Estimation of global air–sea carbon dioxide flux and its regulation mechanism	48	2 293	47.77	2018.3
8	Research on the precision nutrition and healthy engineering	246	25 780	104.80	2018.7
9	Research and development of biomass textile materials for low-carbon environmental protection	101	7 362	72.89	2019.2
10	Research on whole component utilization of bulk biomass	50	697	13.94	2021.4

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in environmental and light textile engineering

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Environmental risks of emerging contaminants in soil	0	1	1	11	51	22
2	Non-CO_2 greenhouse gas emission reduction and utilization	23	24	23	51	54	80
3	Technologies for prevention and remediation of micro-pollution of drinking water sources and safe utilization of micro-polluted water	22	18	24	14	5	1
4	Frontier interpretation of greenhouse gas emissions from aquaculture	1	8	3	8	7	6
5	Neural network-based ensemble prediction method	0	0	0	32	14	4
6	Research on the impact of urbanization on hourly extreme precipitation	3	3	4	15	8	14
7	Estimation of global air–sea carbon dioxide flux and its regulation mechanism	19	9	11	6	3	0
8	Research on the precision nutrition and healthy engineering	57	56	62	46	21	4
9	Research and development of biomass textile materials for low-carbon environmental protection	13	21	21	27	15	4
10	Research on whole component utilization of bulk biomass	0	0	0	8	14	28

synergistic effects. However, multiple contaminants always coexist in soil; besides, a large number of factors may affect the toxicity of contaminant mixtures, making the risk assessment of mixed contaminants a complex task. Therefore, mixture toxicology should be given more attention in future studies. In addition, microplastics in soil can also affect the adsorption, degradation and migration behavior of other contaminants, which is also a hot research topic in recent years.

(2) Non-CO_2 greenhouse gas emission reduction and utilization

Greenhouse gases refer to gases in the atmosphere that can absorb long-wave radiation reflected from the Earth's surface and re-emit radiation, leading to an increase in surface temperature. They mainly include carbon dioxide, methane, nitrous oxide, nitric oxide, sulfur dioxide, carbon monoxide, fluorocarbons, and hydrofluorocarbons. Non-CO_2 greenhouse gas emission reduction and resource utilization mainly refers to measures taken to reduce greenhouse gas emissions and convert waste or by-products into reusable resources, thereby reducing environmental pollution and further reducing resource consumption. Currently, most greenhouse gas utilization schemes focus on carbon dioxide, such as capturing carbon dioxide for enhanced oil recovery and synthetic fuel production.

The concentration of non-CO_2 greenhouse gases in the atmosphere is much lower than that of carbon dioxide, but their global warming potential (GWP) is much higher that of carbon dioxide. There have been some explorations in the resource utilization of non-CO_2 greenhouse gases. Methane can be captured and converted into syngas for the production of synthetic fuels and chemicals such as synthetic natural gas, synthetic oil, synthetic plastics, turning waste gas into higher value-added products. Nitrous oxide can be captured from industrial processes or wastewater treatment through absorption, adsorption, catalytic reduction, etc., and catalytically converted into nitrates for use as agricultural fertilizers or for the production of styrene. Catalytic decomposition of perfluorocarbons can produce decomposition products such as hydrogen fluoride for use in chemical basic products, etc. The reduction and resource utilization of non-CO_2 greenhouse gases are of great significance in promoting pollution reduction, carbon reduction, and comprehensive air pollution control, and it is also one of the frontier research hotspots in environmental science and engineering.

(3) Technologies for prevention and remediation of micro-pollution of drinking water sources and safe utilization of micro-polluted water

The micro-pollution of drinking water sources featuring emergence of trace organic pollutants has become a global environmental concern. Recently, the proposal of the concept of emerging contaminants and the action of emerging contaminant control have put forward higher requirements for the prevention and control of micro-pollution in drinking water sources, and it is urgent to develop technologies for prevention and control and safe utilization of micro-polluted water.

According to different types of treatment technology, this research frontier mainly includes: ① advanced oxidation technologies for the treatment of organic micro-pollutants, including ozone oxidation, Fenton-like oxidation, and electrocatalytic oxidation; ② membrane technologies for treatment of micro-pollution in water sources, including reverse osmosis, forward osmosis, and nanofiltration; ③ research on adsorbents for micro-pollutants, mainly focusing on carbonaceous materials, particularly activated carbon; and ④ biochemical treatment technologies for micro-pollution in water sources, such as biological aerated filter. Among the various micro-pollutants of concern, the treatment methods for per- and polyfluoralkyl substances, medicines and personal care products, disinfection by-products, and microcystins have attracted considerable attention.

A promising field of research in the future is the development of selective advanced oxidation technologies for target micro-pollutants in micro-polluted water sources in light of the substantially lower concentration of the micro-pollutants compared to the coexisting substrates. Currently, this research frontier mainly focuses on the treatment technology of micro-pollutants, while there are few studies on the risk control of water quality of drinking water sources. Hence, it is promising to develop technologies for safe utilization of micro-polluted water based on risk control of water quality.

(4) Frontier interpretation of greenhouse gas emissions from aquaculture

China's marine fisheries economy has advanced stably, with surging carbon emissions from marine fisheries. To integrate the concept of green and low-carbon development into the whole process of marine fisheries development, it is necessary to understand the status quo and development trend of carbon emissions from marine fisheries.

Frontier studies in recent years have used system dynamics methods, decoupled index models and other methods to establish a dynamic model of carbon emissions from marine fisheries, and to study the relationship between carbon emissions and economic output, and the key influencing factors of carbon emissions from China's marine capture fisheries.

It is found that rapid economic development has a significant impact on increasing carbon emissions from marine fisheries, and both fishery carbon emissions and carbon sinks show an increasing trend while net carbon emissions a decreasing one; there are differences in the performance of carbon emissions, carbon sinks and net carbon emissions in different provinces, and the adjustment of the energy and industrial structure can help control carbon emissions from marine fisheries. The decoupling status of all coastal regions has improved in recent years, and the study recommends strengthening the implementation of carbon tax policies, establishing compensation mechanisms for farmers, and promoting carbon emissions trading and international blue carbon trading.

(5) Neural network-based ensemble prediction method

With the development of science and technology, weather forecasting technology has been constantly improved. Since the 1990s, ensemble forecasting, as an important means of reducing prediction uncertainty and improving prediction skills, has become the mainstream method for numerical weather and climate prediction in the world. The core operational logic of ensemble forecasting is to obtain a set of initial numerical forecast values with certain distribution characteristics of probability density function within a range of initial value error by using some certain mathematical methods, and then integrate each initial value with a numerical model to obtain a set of forecast results. From the set of forecast results, the probability density distribution information of future weather states, such as ensemble mean, probability, dispersion, extreme values, is estimated. In recent years, the application of artificial intelligence in the field of meteorology has attracted more and more attention, and neural network is an important branch of it. The main feature of neural network is that the input data can be mapped to the output data through any degree of nonlinearity, and it has a strong ability in learning and fitting highly nonlinear functions. By layer and layer feature transformation, the feature representation of the sample in the original space is transformed into a new feature space, so as to improve the accuracy of classification or prediction. Therefore, the ensemble forecasting method based on intelligent algorithm can fully take advantage of various numerical forecasting models and has a promising prospect of popularization and application in meteorological operations.

(6) Research on the impact of urbanization on hourly extreme precipitation

The occurrence of extreme precipitation often leads to water accumulation and flooding, and even causes landslides, mudslides and other geological disasters, threatening the safety of people's lives and property. Different from long-term extreme precipitation, extreme hourly precipitation can generate a large amount of precipitation in a short period of time, which has more serious impacts on people's lives and economic development. With the development of global urbanization, more and more attention has been paid to the relationship between extreme precipitation changes and urbanization. In urban areas, the factors that affect hourly extreme precipitation changes are very complex, and each factor even has a mutually cancelling effect. Urban heat island effect, aerosol emissions, frictional effect on urban underlying surfaces, and blocking effect of buildings can all affect the original distribution of precipitation in the local area where the city is located. Unlike the impact on temperature, the major centers of the impact may not be concentrated in the urban center, but may vary according to different geographical characteristics and meteorological circulation backgrounds. Therefore, further research on the relationship between extreme hourly precipitation and urbanization is beneficial for better urban engineering design and infrastructure planning. On the other hand, due to the characteristics of small spatial scale, rapid development and great difficulty in forecasting of convective systems that form extreme hourly precipitation, in-depth understanding and correct prediction of such systems are not only the key to improving refined meteorological services, but also helpful to enhance the ability of meteorological disaster prevention and reduction.

(7) Estimation of global air–sea carbon dioxide flux and its regulation mechanism

The ocean is the largest carbon pool in the Earth's system, regulating the amount of carbon in the atmosphere by absorbing and releasing carbon dioxide. The ocean carbon cycle is an important part of the global carbon cycle. In the context of global warming, accurate estimation of the air–sea carbon dioxide flux is an important part of the global carbon cycle and the key part of the global quantitative assessment of the ocean carbon budget and its spatio-temporal pattern of the source-sink. Further clarification of its regulatory mechanism is of great significance for understanding, predicting, and evaluating the global carbon cycle, climate change, and marine ecosystem health, and also provides a scientific basis for protecting the ocean and responding to climate change.

The current methods for studying the air–sea carbon dioxide flux include setting buoys in the ocean to measure the concentration of carbon dioxide in seawater; using satellite remote sensing technology to monitor the partial pressure of carbon dioxide on the ocean surface and estimating the air–sea carbon dioxide flux; on-site sampling and observation by ships and submersibles; laboratory research by radioisotope tracer. However, current data are few, the spatio-temporal distribution is extremely uneven, and the uncertainty of flux estimation is large. In the future, it is necessary to carry out further research on long-term, continuous, and wide-coverage carbon dioxide concentration monitoring, strengthen the development of more accurate means of estimating the air–sea carbon dioxide flux, and deeply explore the factors that regulate the air–sea carbon dioxide flux. Accurate assessment of carbon dioxide flux and a comprehensive analysis of its regulation mechanism are of great practical significance for predicting the ocean's ability to absorb carbon dioxide emitted by humans in the future.

(8) Research on the precision nutrition and healthy engineering

Translating the growing findings of basic nutrition science into clinically beneficial dietary guidance is one of the main challenges in the field of nutrition and health research today. The latest standardized dietary analysis results indicate that there are still huge differences in people's reactions to consuming the same food. This indicates that nutritional interventions need to consider factors such as dietary habits, food behavior, and physical activity/exercise. Precision nutrition aims to identify metabolic heterogeneity factors in individuals through multiple omics methods such as genetics, epigenetics, microbiome, metabolomics, and environmental exposure. In addition, based on methods such as molecular biology and molecular nutrition, precision nutrition conducts screening of biomarkers related to nutritional metabolism, studies the molecular and pathological processes of diseases, identifies precise targets for different health problems, and identifies the precise needs of different populations. Ultimately, precise nutritional stratification standards for populations are established, so as to achieve better dietary guidance and intervention and realize the goal of reversing chronic diseases and maintaining healthy homeostasis.

(9) Research and development of biomass textile materials for low-carbon environmental protection

Biomass materials consist of organic macromolecules obtained from living things, including plants, animals, and microbes. These materials are generally composed of carbon, hydrogen, and oxygen. In their original form, these materials undergo biodegradation easily due to the presence of natural microbial agents in the environment. This process results in the production of water, carbon dioxide, and other small molecular byproducts, allowing for their reintegration into the natural cycle. The unique characteristic of biomass materials grants them considerable benefits, making them intrinsically equipped with notable capacities for both regeneration and biodegradation. The common biomass materials are lignin and its derivatives, modified starch, chitin and its derivatives, tea saponin and its derivatives, fat peptide matter, etc., which have broad application prospects in the fields of textile slurry, textile functional finishing, textile printing and dyeing wastewater treatment.

The growing consumer expectations have led to a heightened focus on the usability of textile materials, specifically intelligent textile goods. Traditional textile materials have, during their manufacturing process, utilized significant amounts of natural resources, resulting in excessive carbon emissions. The increasing scarcity of conventional textile raw materials, such as chemical fibers and wool, has led to a growing interest in biomass materials. These materials are attractive due to their abundant availability, lower costs, and desirable physical-chemical stability, mechanical properties, and environmental compatibility. The endeavor to produce biomass textile materials that are low in carbon emissions and ecologically benign is crucial to tackle resource constraint in the textile industry and promote sustainable development. Therefore, the scientific importance of these materials is substantial.

The development and application of biomass materials face challenges due to their diverse sources and intricate composition. These factors impede the progress in utilizing biomass materials. Consequently, there is a need to explore low-carbon and environment-friendly methods for efficient purification. Additionally, chemical or physical modifications can be employed to align biomass materials with societal requirements. Furthermore, there is a growing interest in investigating the broader utilization of biomass materials in the textile industry, making it a prominent area of current research.

(10) Research on whole component utilization of bulk biomass

The entire life cycle of industrial production is usually accompanied by carbon emission issues, in which the mass production and usage of industrial raw materials such as iron and steel, cement as well as petroleum-based polymer materials account for a considerable proportion of the total carbon emissions. Therefore, the industrial feedstock substitution has become a key technology in the field of resource carbon neutrality. According to the International Energy Agency (IEA), biomass refers to a variety of organisms formed using photosynthesis to sequester carbon, which is a typically renewable carbon-neutral resource. Therefore, it is strategically important for achieving the goal of carbon neutrality through utilizing biomass as a full or partial replacement of feedstock for heavy carbon industries. Biomass has a complex composition, and there are large differences in the physical structure and chemical properties of various components. Hence, the conventional technological strategies for biomass utilization usually require the separation of biomass components, followed by utilization in a graded and qualitative manner. However, it is difficult to efficiently separate various biomass components since it requires harsh experimental conditions and consumes large quantities of chemicals, which further leads to the carbon emission problem. In addition, the components of biomass feedstock that cannot be utilized after separation also cause resource waste and environmental pollution problems. Therefore, the efficient utilization of all components of bulk biomass in industrial production is expected to further solve the problem of carbon emissions. In the future, it is necessary to focus on the research and development of pre-treatment technologies as well as processing and molding technologies that are universally applicable to various types of bulk biomass, so as to meet the needs of practical production while realizing the goal of resource carbon neutrality.

1.2 Interpretations for three key engineering research fronts

1.2.1 Environmental risks of emerging contaminants in soil

Emerging contaminants are toxic and harmful chemicals generated in human activities such as production and daily life, mainly including endocrine disruptors (EDs), pharmaceuticals and personal care products (PPCPs), perfluorinated compounds (PFCs), brominated flame retardants (BRPs), disinfection by-products of drinking water, nanomaterials, and microplastics. Emerging contaminants have characteristics such as persistence, high harm, and wide distribution. Its concentration in soil is generally low, but it poses serious harm to the ecosystem and has a significant impact on human health.

Soil is a huge "sink" of emerging contaminants in terrestrial ecosystems. For example, the amount of microplastics released into the soil every year is 4–23 times more than that released into the ocean. Only in Europe and North America do microplastics accumulate in the soil every year 7×10^5 tons, far exceeding the total amount of microplastics in the global ocean (9.3×10^4–2.3×10^5 tons). After entering the soil, some emerging contaminants remain in the soil or accumulate in plants and soil animals, while the other part enters surface water and groundwater through horizontal and vertical migration, which may eventually be exposed to humans. Therefore, soil is the "source" of emerging contaminants in the ecosystem.

Emerging contaminants affect the cycling of soil nutrients by altering soil physicochemical properties, reducing soil fertility, and interfering with the functional and structural diversity of soil microbial communities. In addition, certain toxic effects of emerging contaminants on soil animals, plants, and microorganisms, such as oxidative stress, DNA damage, and reduced metabolic function, will further threaten human health and life through the food chain. Research reports indicate that microplastics can lead to oxidative stress and inflammatory reactions upon entry into the human body, as well as their persistent presence in the body that may lead to chronic inflammation and increase the risk of tumor development.

Microplastics and antibiotics are research hotspots in the environmental risks of soil emerging contaminants. The dynamics and fate of emerging contaminants entering the soil, as well as the bioavailability of emerging contaminants in the soil environment, are currently the main issues of concern.

It can be seen from Table 1.2.1 that the main output countries of the core papers in this research direction are China, Iran, Turkey, Peru, and India. Among them, China ranks first in the number of core papers, accounting for 33.72%; Iran came second, accounting for 27.91%. The total number of core papers from the above two countries accounts for nearly 60% of the global total. According to Table 1.2.2, the institutions with a large number of core papers produced in this front are Hunan University, Quchan University of Technology, Akdeniz University, Universidad San Ignacio de Loyola, Hunan University of Chinese Medicine, Shiraz University of Medical Sciences, and Bushehr University of Medical Sciences. The number of core papers from these institutions has exceeded 8.

It can be seen from Figure 1.2.1 that China, Iran, Turkey, India, Malaysia, the USA, and Egypt pay more attention to cooperation among countries in this research field. China has the largest number of published papers, mainly in cooperation with Iran and Turkey. From Figure 1.2.2, it can be seen that institutions such as Quchan University of Technology, Akdeniz University, Shiraz University of Medical Sciences, University of Electronic Science and Technology of China, and Ankara University have established cooperative relationships.

In Table 1.2.3, the country with the highest output of citing papers is China, with a high percentage of citing papers 39.39%; India came second at 11.31%; Iran ranks third at 10.78%. In Table 1.2.4, the institution that produces the most citing papers is the Chinese Academy of Sciences, with 18.20% of the citing papers, and Quchan University of Technology has 14.82% of the citing papers.

Based on the above data analysis results, it can be seen that China ranks among the world's top in terms of core paper output and citation quantity in terms of environmental risks of new pollutants in soil, with a relatively large number of core papers cited by Chinese research institutions. Figure 1.2.3 shows the roadmap of the engineering research front of "environmental risks of emerging contaminants in soil".

Table 1.2.1 Countries with the greatest output of core papers on “environmental risks of emerging contaminants in soil”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	29	33.72	2 276	78.48	2020.8
2	Iran	24	27.91	1 192	49.67	2021.5
3	Turkey	17	19.77	994	58.47	2021.5
4	Peru	13	15.12	376	28.92	2021.5
5	India	12	13.95	436	36.33	2021.3
6	Malaysia	11	12.79	603	54.82	2020.8
7	USA	8	9.30	446	55.75	2020.9
8	Egypt	8	9.30	327	40.88	2021.0
9	Germany	8	9.30	211	26.38	2021.2
10	Saudi Arabia	7	8.14	136	19.43	2021.4

Table 1.2.2 Institutions with the greatest output of core papers on “environmental risks of emerging contaminants in soil”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Hunan University	15	17.44	923	61.53	2020.7
2	Quchan University of Technology	12	13.95	906	75.50	2021.7
3	Akdeniz University	10	11.63	870	87.00	2021.5
4	Universidad San Ignacio de Loyola	9	10.47	311	34.56	2021.3
5	Hunan University of Chinese Medicine	8	9.30	503	62.88	2020.6
6	Shiraz University of Medical Sciences	8	9.30	479	59.88	2021.5
7	Bushehr University of Medical Sciences	8	9.30	205	25.62	2021.2
8	University of Electronic Science and Technology of China	7	8.14	746	106.57	2021.7
9	Universiti Teknologi Malaysia	7	8.14	317	45.29	2020.9
10	Ankara University	7	8.14	230	32.86	2021.3

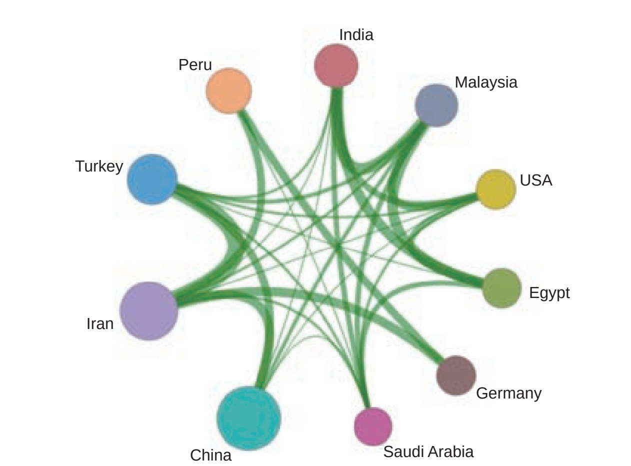

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “environmental risks of emerging contaminants in soil”

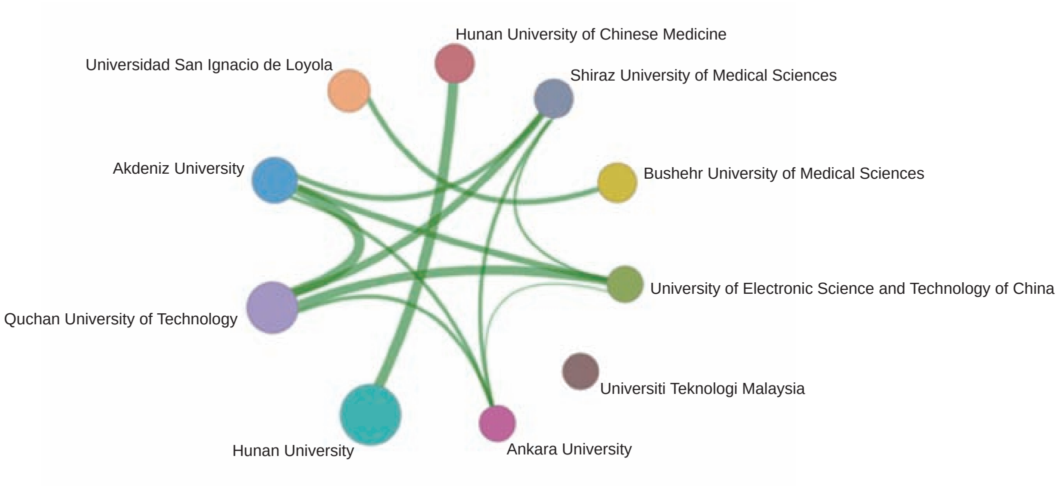

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “environmental risks of emerging contaminants in soil”

Table 1.2.3 Countries with the greatest output of citing papers on “environmental risks of emerging contaminants in soil”

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 125	39.39	2021.6
2	India	323	11.31	2021.7
3	Iran	308	10.78	2021.8
4	USA	226	7.91	2021.5
5	Republic of Korea	169	5.92	2021.7
6	Turkey	142	4.97	2021.8
7	Saudi Arabia	135	4.73	2021.6
8	Canada	116	4.06	2021.5
9	UK	110	3.85	2021.4
10	Malaysia	103	3.61	2021.5

Table 1.2.4 Institutions with the greatest output of citing core papers on “environmental risks of emerging contaminants in soil”

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	97	18.20	2021.5
2	Quchan University of Technology	79	14.82	2021.9
3	Hunan University	51	9.57	2021.2
4	Islamic Azad University	50	9.38	2021.8
5	King Saud University	50	9.38	2021.8
6	University of Johannesburg	41	7.69	2021.8
7	University of Electronic Science and Technology of China	40	7.50	2021.7
8	University of Tabriz	36	6.75	2021.9
9	Shenzhen University	31	5.82	2020.7
10	Akdeniz University	30	5.63	2021.8

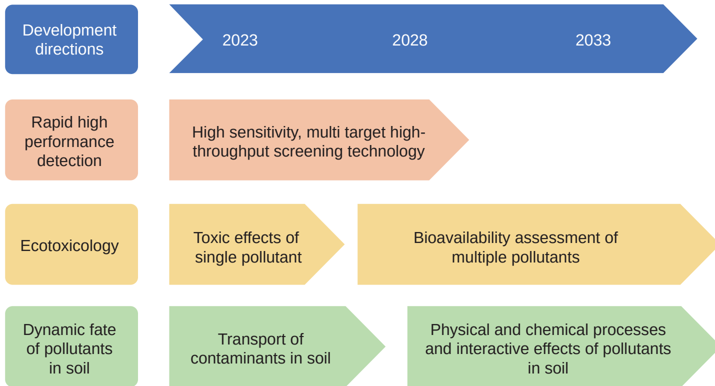

Figure 1.2.3 Roadmap of the engineering research front of “environmental risks of emerging contaminants in soil”

1.2.2 Neural network-based ensemble prediction method

Ensemble forecasting is an important way to reduce forecasting uncertainty and improve forecasting skills. Since the 1990s, ensemble forecasting has become the mainstream method for numerical weather forecast and climate prediction in the world. The concept of ensemble prediction is to generate a set of prediction results for a specific target. Its core is to make repeated forecasts through multiple initial sets with little difference without changing the existing forecast model, so as to increase the reliability of the forecast results. Its ultimate goal is to quantitatively predict the probability distribution of variable states in the future. Neural networks have a strong ability to deal with nonlinear problems, mainly using big data to learn features and being able to depict the rich internal information of data. However, current ensemble prediction methods based on neural networks often predict a specific meteorological data, which has limitations and cannot utilize the correlation between multiple types of weather data for prediction, resulting in low prediction efficiency.

The main countries with the greatest output of core papers on “neural network-based ensemble prediction method” are shown in Table 1.2.5. It can be found that China ranks first in both the proportion of papers and citations, and there is a big gap between other countries and China, which shows that China has a strong research advantage in this field. The USA ranks second in the number of core papers, and Iran ranks third. From the perspective of the citations per paper, China ranks low; and the number of core papers in Australia is small, but the citations in Australia ranks first, which also shows the importance of publishing high-level core papers recognized by peers. As shown in Figure 1.2.4, China has shown close cooperation with the USA, but the cooperation with other countries should be strengthened. Table 1.2.6 shows the main output institutions for core papers in this engineering research front. In terms of the number of core papers, the No.1 institution is Duy Tan University. As shown in Figure 1.2.5, the institutions in the same country has worked in cooperation, but there’s very little cooperation among these 10 institutions.

In the rankings of countries with the greatest output of citing papers, China, the USA, and India rank the top three (Table 1.2.7). Chinese Academy of Sciences ranks first among the institutions, followed by North China Electric Power University and Huazhong University of Science and Technology (Table 1.2.8). It can be seen that China is ahead of the rest of the world in the study of “neural network-based ensemble prediction method”. Meanwhile, the Chinese Academy of Sciences is also in a leading position among the research institutions in this field, and should continue to maintain a relevant research focus on this front. In addition, the cooperation with other countries should be strengthened.

Figure 1.2.6 shows the roadmap of the engineering research front of “neural network-based ensemble prediction method”. It can be seen that there are two key development stages that this research front will experience in the next 5–10 years. The first is to set different model parameters for different meteorological data on the basis of obtaining sufficient training data, and perform multiple rounds of iterations to obtain better prediction accuracy. The second stage is to apply neural network methods to ensemble forecasting research to obtain more reliable results.

Table 1.2.5 Countries with the greatest output of core papers on “neural network-based ensemble prediction method”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	22	44.00	1 978	89.91	2020.5
2	USA	9	18.00	756	84.00	2020.4
3	Iran	7	14.00	758	108.29	2020.3
4	Italy	5	10.00	610	122.00	2020.4
5	India	5	10.00	557	111.40	2020.8
6	UK	5	10.00	444	88.80	2020.6
7	Vietnam	4	8.00	512	128.00	2020.8
8	Australia	3	6.00	516	172.00	2020.3
9	France	3	6.00	436	145.33	2020.7
10	Germany	3	6.00	239	79.67	2021.0

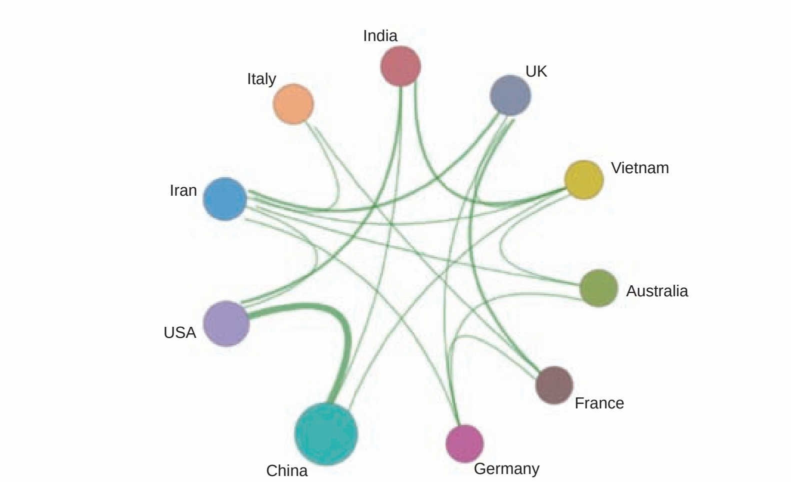

Figure 1.2.4 Collaboration network among major countries in the engineering research front of “neural network-based ensemble prediction method”

Table 1.2.6 Institutions with the greatest output of core papers on “neural network-based ensemble prediction method”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Duy Tan University	3	6.00	412	137.33	2020.3
2	Ton Duc Thang University	2	4.00	323	161.50	2020.5
3	Huazhong University of Science and Technology	2	4.00	288	144.00	2020.0
4	Graduate University of Advanced Technology	2	4.00	228	114.00	2020.0
5	Xi’an Jiaotong University	2	4.00	206	103.00	2021.0
6	North China Electric Power University	2	4.00	156	78.00	2020.0
7	Peking University	2	4.00	153	76.50	2020.5
8	University of Electronic Science and Technology of China	2	4.00	137	68.50	2020.5
9	Tsinghua University	2	4.00	132	66.00	2020.0
10	International University of Business Agriculture and Technology	1	2.00	328	328.00	2020.0

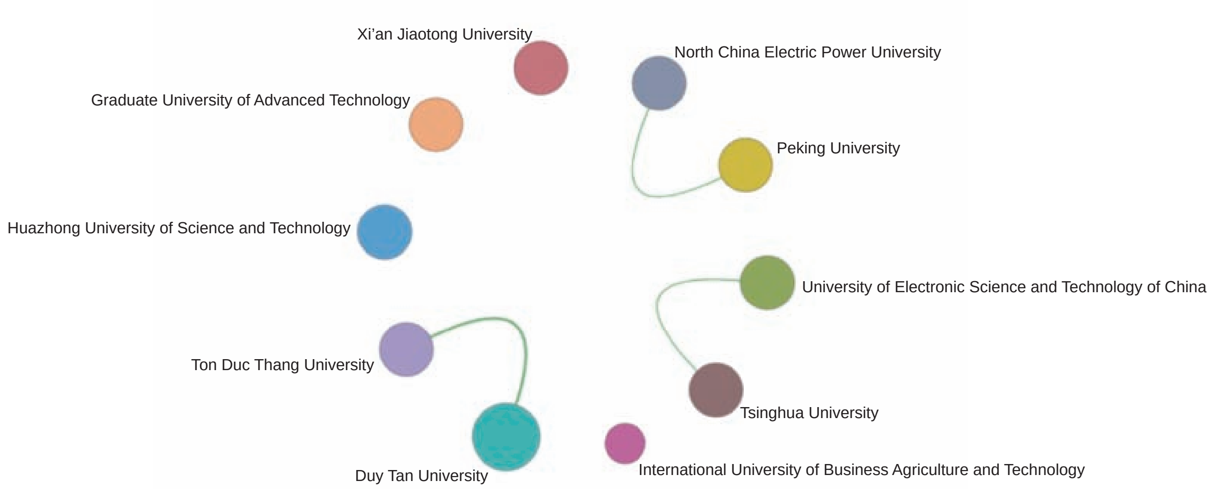

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "neural network-based ensemble prediction method"

Table 1.2.7 Countries with the greatest output of citing papers on "neural network-based ensemble prediction method"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	6 972	47.92	2021.0
2	USA	1 636	11.24	2020.9
3	India	1 094	7.52	2021.3
4	Iran	937	6.44	2020.9
5	UK	735	5.05	2020.9
6	Australia	634	4.36	2020.9
7	Republic of Korea	632	4.34	2021.1
8	Saudi Arabia	554	3.81	2021.4
9	Canada	520	3.57	2021.0
10	Spain	433	2.98	2020.8

Table 1.2.8 Institutions with the greatest output of citing papers on "neural network-based ensemble prediction method"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	404	17.71	2021.1
2	North China Electric Power University	331	14.51	2020.5
3	Huazhong University of Science and Technology	206	9.03	2020.5
4	Tsinghua University	202	8.86	2021.0
5	Wuhan University	188	8.24	2021.1
6	Hohai University	176	7.72	2021.1
7	Tianjin University	161	7.06	2020.8
8	Duy Tan University	161	7.06	2020.3
9	Islamic Azad University	152	6.66	2020.9
10	Central South University	151	6.62	2021.2

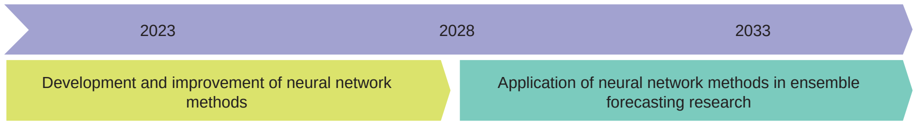

Figure 1.2.6 Roadmap of the engineering research front of “neural network-based ensemble prediction method”

1.2.3 Research on the precision nutrition and healthy engineering

Translating the growing findings of basic nutrition science into clinically beneficial dietary guidance is one of the main challenges in the field of nutrition and health research today. The latest standardized dietary analysis results indicate that even when consuming the same food, there are still significant differences in people’s reactions. This indicates that nutritional interventions need to consider such factors as dietary habits, food behavior, and physical activity/exercise.

Therefore, the frontier path for the intelligent implementation of precision nutrition and shaping the paradigm of nutritional life lies in exploring the interaction between the intake of different nutritional factors, different metabolic characteristics, and different individual environments, and forming precision nutrition intervention methods with wearable devices as a lifestyle, which is achieved by combining deep phenotypes such as nutrigenomics, metabolomics, and microflora with the blood indicators (such as blood oxygen, blood pressure, blood sugar.) before and after diet, as well as physiological phenotypes such as faecal flora and dietary behavior rules, personal activities/exercise, and other life factors, leveraging the advantages of big data analysis and machine learning, techniques such as regression, classification, recommendation and clustering can also be employed. For example, recent research on obesity phenotypes has revealed that genetic variation, microbial metabolites, and epigenetic factors are crucial for obesity phenotypes. The epigenetic factors include variations in genes such as FTO, MC4R, PPAR, apoA, and fads, DNA methylation in the CpG island region, and specific miRNAs and microbial species such as Firmicut, Bacteriodes, and Clostridies. Additionally, microbial metabolites, folic acid, B-vitamins, and short-chain fatty acids interact with miRNAs, further affecting the obesity phenotype, which highlights the comprehensive nature of nutrient metabolism imbalance influenced by multi-dimensional biological factors. Therefore, it is crucial to integrate genomics, proteomics, metabolomics, microbiology, and other techniques to explore deep molecular indicators and biomarkers of diseases related to nutritional imbalance, and to establish a predictive analysis and clustering basis for abnormal metabolic indicators in the population from a multi-omics perspective. Such an approach can guide the preventive intervention of precision nutrition for chronic diseases and metabolic disorders, which is also the inevitable direction of clinical development in the field of precision nutrition.

Precision nutrition aims to identify metabolic heterogeneity factors in individuals through multiple omics methods such as genetics, epigenetics, microbiome, metabolomics, and environmental exposure. In addition, based on methods such as molecular biology and molecular nutrition, precision nutrition conducts screening of biomarkers related to nutritional metabolism, studies the molecular and pathological processes of diseases, identifies precise targets for different health problems and the targeted needs of populations. Ultimately, precise nutritional stratification standards for populations are established, so as to achieve better dietary guidance and intervention and realize the goal of reversing chronic diseases and maintaining healthy homeostasis.

Table 1.2.9 shows the countries with the greatest output of core papers on “research on the precision nutrition and healthy engineering”. Among them, China ranks sixth with 11.79% core papers and 2 556 citations. There is still a gap compared to other countries, indicating that China needs to strengthen its research advantages in this area. Canada has fewer core papers, but it ranks first in terms of citations per paper. This indirectly illustrates the importance of publishing high-quality core papers recognized by peers. Table 1.2.10 shows the institutions with the greatest output of core papers on “research on the precision nutrition and healthy engineering”. None of the Top 10 institutions are from China. Harvard University ranks first with 25 core papers. According to Figure 1.2.7, the countries that prioritize cooperation in this research field are the USA, the UK, Germany, and New Zealand. Figure 1.2.8 shows there is significant cooperation between Harvard University and Brigham and Women’s Hospital. Table 1.2.11 indicates that the country with the greatest output of citing papers is the USA, accounting for a significant proportion of 23.61%. China ranks second with 20.54%. In Table 1.2.12, Harvard University is the institution with the largest output of citing papers, with

Table 1.2.9 Countries with the greatest output of core papers on "research on the precision nutrition and healthy engineering"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	97	39.43	10 192	105.07	2018.7
2	Italy	42	17.07	6 707	159.69	2018.9
3	UK	40	16.26	5 676	141.90	2018.5
4	Spain	34	13.82	3 559	104.68	2018.6
5	Germany	29	11.79	5 245	180.86	2018.7
6	China	29	11.79	2 556	88.14	2018.5
7	Netherlands	26	10.57	4 290	165.00	2018.6
8	France	23	9.35	4 097	178.13	2018.7
9	Canada	22	8.94	4 120	187.27	2018.3
10	Australia	20	8.13	3 301	165.05	2018.2

Table 1.2.10 Institutions with the greatest output of core papers on "research on the precision nutrition and healthy engineering"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	25	10.16	3 841	153.64	2018.8
2	Tufts University	11	4.47	1 235	112.27	2018.8
3	University of Navarra	10	4.07	1 436	143.60	2018.0
4	Brigham and Women's Hospital	10	4.07	1 091	109.10	2019.4
5	Carlos III Health Institute	9	3.66	821	91.22	2018.1
6	Newcastle University	9	3.66	732	81.33	2017.4
7	University of Oxford	8	3.25	1 414	176.75	2019.5
8	University of Copenhagen	8	3.25	487	60.88	2018.1
9	University of Milan	7	2.85	1 807	258.14	2019.0
10	Maastricht University	7	2.85	569	81.29	2017.4

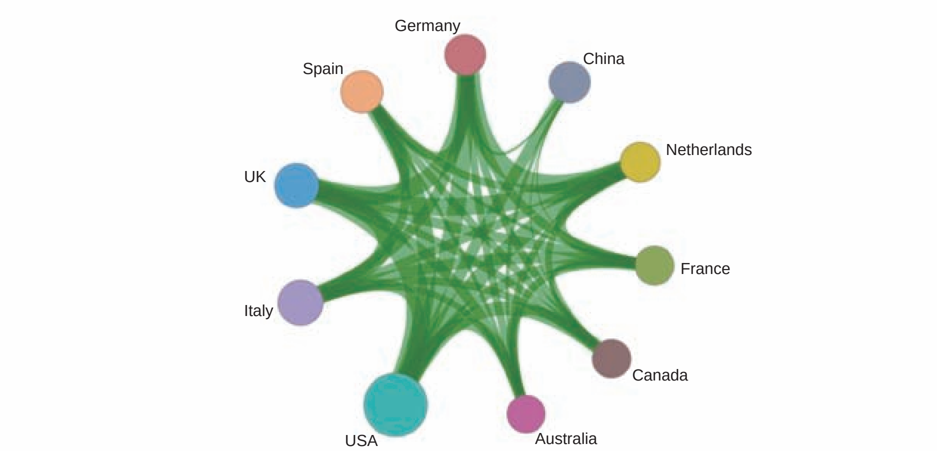

Figure 1.2.7 Collaboration network among major countries in the engineering research front of "research on the precision nutrition and healthy engineering"

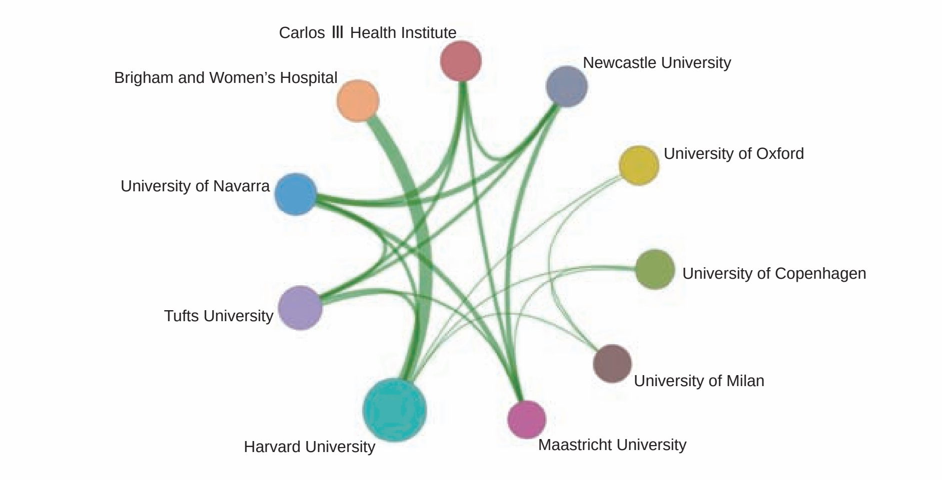

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "research on the precision nutrition and healthy engineering"

Table 1.2.11 Countries with the greatest output of citing papers on "research on the precision nutrition and healthy engineering"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	USA	5 160	23.61	2020.9
2	China	4 489	20.54	2021.2
3	Italy	2 209	10.11	2020.9
4	UK	1 900	8.69	2020.8
5	Spain	1 716	7.85	2020.9
6	Germany	1 484	6.79	2020.9
7	Australia	1 228	5.62	2020.8
8	Canada	1 034	4.73	2020.9
9	France	905	4.14	2020.9
10	Netherlands	898	4.11	2020.8

Table 1.2.12 Institutions with the greatest output of citing papers on "research on the precision nutrition and healthy engineering"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Harvard University	615	21.39	2020.9
2	Chinese Academy of Sciences	405	14.09	2021.2
3	University of Milan	279	9.70	2021.0
4	University of Queensland	216	7.51	2020.6
5	University of Sao Paulo	211	7.34	2020.8
6	University of Copenhagen	209	7.27	2020.7
7	Zhejiang University	201	6.99	2021.3
8	University of Toronto	187	6.50	2021.0
9	University of Naples Federico II	187	6.50	2020.8
10	Carlos III Health Institute	184	6.40	2020.6

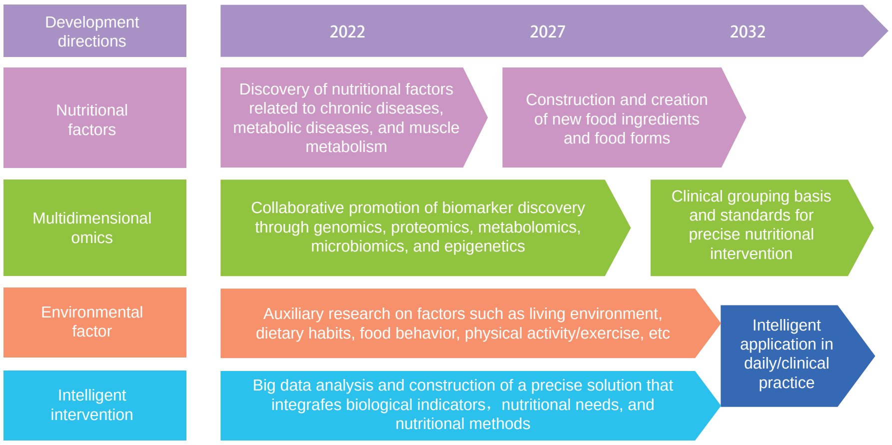

Figure 1.2.9 Roadmap of the engineering research front of “research on the precision nutrition and healthy engineering”

a proportion of 21.39%. It is followed by Chinese Academy of Sciences, with a proportion of 14.09%.

Based on the above data analysis, it can be concluded that among the top countries in terms of citations of core papers on “research on the precision nutrition and healthy engineering”, China ranks second only to the USA. However, there is still a significant gap between China and other countries like the USA in terms of core paper output.

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

The Top 10 engineering development fronts in the field of environmental and light textile engineering are summarized in Table 2.1.1, 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 2017 and 2022 is presented in Table 2.1.2.

(1) Low-carbon source wastewater denitrification technology

Nitrogen pollution is a typical global environmental issue that has long posed a threat to human health and aquatic ecosystem safety. Increasingly stringent standards on sewage discharge have raised higher requirements for nitrogen emissions from wastewater. In traditional nitrate removal processes based on heterotrophic denitrification, microorganisms utilize organic carbon sources as electron donors to convert nitrates into harmless nitrogen gas. During this process, denitrification performance strongly depends on the concentration of organic carbon sources in water. However, there is a widespread shortage of carbon sources in urban wastewater treatment plants, which adversely affects total nitrogen removal and results in unstable effluent compliance. Therefore, the development of new low-carbon nitrogen removal technologies for wastewater has become a research hotspot.

In recent years, with the deepening understanding of the biological denitrification mechanism, novel denitrification processes such as sulfur-based autotrophic denitrification, shortcut nitrification-denitrification, simultaneous nitrification-denitrification, and anaerobic ammonia oxidation have been developed. These processes focus on shortening the denitrification pathway to achieve deep denitrification while reducing carbon source requirements and operational costs. Although these corresponding processes have been pilot-tested in hundreds of wastewater treatment plants worldwide, research on these new denitrification technologies is still in its infancy. Their practical application in engineering requires further development and exploration. The key factors influencing the processes and future research directions encompass two primary elements. Firstly, in comparison to conventional heterotrophic denitrifying bacteria, autotrophic bacteria exhibit slow growth rates, resulting in extended startup times. Therefore,

Table 2.1.1 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-carbon source wastewater denitrification technology	941	2 933	3.12	2020.0
2	River and lake eutrophication ecological management technology and equipment	463	802	1.73	2019.7
3	Cross media collaborative prevention and control technology for emerging and traditional pollutants	1 000	4 957	4.96	2019.7
4	Integrated soil pollution reduction and carbon emission control technologies for chemical industrial park	942	2 947	3.13	2020.3
5	Laser detection technology of bio-optical profile in upper ocean water	431	1 393	3.23	2019.7
6	Development of a regional earth system model with convective resolution scale	9	7	0.78	2020.9
7	Construction technology of large-scale aquaculture platform in deep sea	72	108	1.5	2020.5
8	Antimicrobial textile derived from cellulose	1 000	3 941	3.94	2020.8
9	Research on the bioaugmentation of food functional components	829	971	1.17	2020.6
10	Cell factory technology for sustainable production of lactic acid from lignocellulose	68	1 817	26.72	2019.0

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in environmental and light textile engineering

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Low-carbon source wastewater denitrification technology	96	116	151	164	175	239
2	River and lake eutrophication ecological management technology and equipment	64	83	75	67	76	98
3	Cross media collaborative prevention and control technology for emerging and traditional pollutants	136	147	165	157	197	198
4	Integrated soil pollution reduction and carbon emission control technologies for chemical industrial park	86	119	112	115	171	339
5	Laser detection technology of bio-optical profile in upper ocean water	55	66	63	81	92	74
6	Development of a regional earth system model with convective resolution scale	0	1	0	2	2	4
7	Construction technology of large-scale aquaculture platform in deep sea	3	7	4	17	22	19
8	Antimicrobial textile derived from cellulose	52	64	60	71	394	359
9	Research on the bioaugmentation of food functional components	59	76	87	83	154	370
10	Cell factory technology for sustainable production of lactic acid from lignocellulose	16	16	15	6	6	9

it is imperative that research focuses on the biological and physiological characteristics of bacterial strains. Additionally, efforts should be directed towards the domestication, cultivation, and preservation of these strains. Secondly, the accumulation of nitrite plays a pivotal role in achieving low-carbon nitrogen removal. Consequently, optimizing design parameters, such as pH, dissolved oxygen, and influent conditions, to enhance shortcut nitrification reactions represents a crucial avenue for process improvement.

(2) River and lake eutrophication ecological management technology and equipment

Eutrophication of river and lake refers to the phenomenon of water pollution caused by excessive content of nitrogen, phosphorus and other nutrients in water. The essence is that the destroyed balance of nutrient salt migration and transformation in river and lake water bodies results in community composition disorder, species distribution imbalance and nutrient structure instability in river and lake water ecosystems, which hinders the flow of matter and energy in the system and makes the whole water ecosystem tend to collapse. The sources of nutrients such as nitrogen and phosphorus in rivers and lakes are complex, including both endogenous and exogenous sources, both point and non-point sources, causing great difficulties in the treatment of eutrophication in rivers and lakes. Regardless of the source of nutrients, the formation of water eutrophication is affected by many factors, including both natural factors and man-made factors. Effective control of exogenous pollution is the basis of controlling river and lake eutrophication. By regulating the structure of aquatic ecosystem, a complete nutrient level of ecosystem is built; natural, healthy and stable functions of aquatic ecosystem are restored; resistance to external interference is enhanced; and aquatic ecosystem is kept in an environmentally benign and sustainable cycle. Therefore, ecological management technology, that is, improving the biological purification function of water body through internal regulation, is an important research direction to solve the eutrophication of rivers and lakes.

(3) Cross media collaborative prevention and control technology for emerging and traditional pollutants

The composite superposition effect of multiple pollutants in industrial, agricultural, and urban areas is prominent, and the mutual transformation and transmission of multi medium pollutants such as atmosphere, soil, surface water, and groundwater are significant. Further improvement of ecological environment quality cannot be achieved solely through pollution control through a single medium and single element. The disciplinary differentiation of “water pollution control”, “air pollution control”, and “soil pollution control” has led to boundary solidification, often resulting in taking stopgap measures, causing pollutants not to be removed from the environment, but to be transmitted between air, liquid, and solid media, increasing the difficulty of improving environmental quality. Due to the lack of a unified joint pollution control mechanism for cross medium pollution, disconnection in pollution control is quite serious. Based on the results of research on cross media transmission mechanisms and processes, a cross media transmission model for emerging and traditional pollutants is established by using numerical simulation and other methods to simulate the migration process of emerging and traditional pollutants in media such as atmosphere, soil, surface water, and groundwater. The mechanism of regulation and governance of pollutants across media among solid waste, water, air, soil is studied; a cross media collaborative governance technology system for emerging and traditional pollutants is constructed; an efficient, economical, and safe pollution multi medium combination technology optimization and collaborative remediation mechanism is established. These moves aim to break through the cross medium collaborative monitoring technology system for emerging and traditional pollutants, to monitor the distribution and changes of emerging and traditional pollutants in different media, to evaluate prevention and control effects and environmental risks, thus providing theoretical and technological support for achieving cross medium collaborative prevention and control of emerging and traditional pollutants.

(4) Integrated soil pollution reduction and carbon emission control technologies for chemical industrial park

Currently, there are over 22 000 industrial parks in China, more than 600 chemical industrial parks and over 200 provincial-level chemical parks, including petrochemical, fine chemical, pesticide chemical. Some chemical park sites cause severe soil and groundwater pollution, characterized by multiple sources of pollution, multiple generations of cumulative pollution, and multi medium composite pollution. Potential risk management is difficult, and sudden site soil pollution incidents occur from time to time. In addition, the total energy consumption and carbon emissions of the chemical industry account for 12% and 13% of the national total, respectively. Pollution and carbon are highly homologous, and the source sink mechanism is complex, seriously affecting the surrounding environment. Therefore, it is urgent to develop collaborative governance technologies for soil pollution reduction and carbon reduction in chemical park sites, and implement pollution reduction and carbon reduction and pollution prevention in chemical industry parks to realize synchronized production, control and restoration; and conduct precise identification and pollution tracing for retired chemical parks to achieve risk control, green restoration, and safe utilization. Existing technologies only focus on single approach to pollution reduction or carbon reduction, lacking an integrated solution of source control, process control, end treatment, and safe utilization for the overall system. Therefore, it is necessary to establish a refined and intelligent management platform for chemical parks based on material flow and energy flow, develop collaborative disposal technologies and equipment for soil and groundwater pollution in chemical parks with multi medium processes, and use collaborative physicochemical and bioremediation technologies to treat soil pollution in chemical parks. Chemical park site classification and grading management and remediation should be carried out, and management system for pollution tracing, remediation and green development need to be constructed, and a new collaborative governance model for pollution reduction and carbon reduction in chemical industrial parks should be established.

(5) Laser detection technology of bio-optical profile in upper ocean water

The acquisition of three-dimensional data of marine water bodies is a fundamental demand problem that need to be solved urgently in the research of multi-sphere coupling of the Earth system and marine science. The existing marine remote sensing technology is generally two-dimensional plane remote sensing, which has a huge gap with the three-dimensional detection requirements of water profile structure or material and energy migration and spatial and temporal distribution required by marine business and scientific applications. Laser radar can obtain the profile information of bio-optical parameters of upper ocean water by emitting laser to seawater and measuring the spectrum, waveform, intensity and frequency shift of time resolution echo signal. It is a necessary way to realize remote sensing from sea surface to water profile structure. It is an important development direction of satellite ocean remote sensing and an international frontier in the field of ocean optics and water color remote sensing.

The space-borne ocean profile detection technology has not yet broken through, so it can only rely on expensive and sparse field observation methods, which seriously restricts the range and accuracy of satellite ocean remote sensing observation. It is urgent to develop space-borne laser ocean high-precision profile detection technology to realize large-scale remote sensing detection of key parameters of global upper ocean profile and realize the leap from two-dimensional to three-dimensional ocean remote sensing. At present, the main research directions and development trends include: First, the development of new laser detection technologies such as blue-green multi-wavelength, high spectral resolution, and single-photon detection of ocean profiles; second, develop a three-dimensional laser radar radiation transmission simulation technology coupled with complex marine environment and remote sensors; third, develop high-precision lidar ocean optical and biological parameter profile inversion, active and passive fusion and authenticity verification technology; fourth, carry out the application technology of marine laser in frontier science, ecological environment and carbon cycle, and form engineering and large-scale application.

(6) Development of a regional earth system model with convective resolution scale

Regional earth system model and convective resolution scale simulations are two important development directions for regional climate model. Based on the regional climate model, the regional earth system model further considers the biogeochemical cycles such as carbon and nitrogen cycles in the climate system. Its core remains the multi-layer coupled physical climate system of atmosphere-ocean-land-ice. The convective resolution model ($\leq$ 4 km model) no longer requires parameterization of deep convective processes and can provide more realistic terrain, land cover, and explicit description of convective processes, resulting in a more reliable and process-based medium and small-scale climate. Therefore, it is considered an important way to reduce the uncertainty and errors. With the widespread demand for refined regional climate information and the rapid development of high-performance computing resources in recent years, developing convection-resolved scale regional earth system models is needed to accurately describe and predict the impact of climate change and human activities on land surface physical, biological, and geochemical processes, and to improve the understanding of complex interactions between the various layers. It can also provide strong scientific support for weather/climate prediction, climate change adaptation and mitigation, disaster prevention and mitigation and so on.

(7) Construction technology of large-scale aquaculture platform in deep sea

The large-scale aquaculture platform in deep sea is a fishery production comprehensive platform based on marine engineering equipment, industrial aquaculture, marine biological resources development and processing application technology, integrating marine large-scale aquaculture, large-scale breeding of famous and excellent seedlings, fish harvesting and material replenishment, and aquatic product classification and storage. The development and application of the platform have important strategic significance for driving china's marine aquaculture industry from the offshore to the deep sea, creating a "blue granary" and contributing to build china into a strong maritime country.

In recent years, the construction technology of large-scale aquaculture platform in china has been innovating and developing in the direction of information, intelligence and integration. The research and development of specialized deep-sea large-scale aquaculture cage facilities, offshore stability and hydrodynamic control technology of aquaculture platform, intelligent equipment and systems such as automatic precision feeding, water quality monitoring, red tide protection, automatic control technology. In the future, it is necessary to constantly promote the development and application of equipment and facilities for the whole process of "breeding-fishing-processing", further study the hydrological law of deep sea and the construction of aquaculture environment, build a collaborative control and big data management system for deep sea large-scale aquaculture platforms, establish a multi-energy supply and energy security management system and build the whole process industrialization control system and the operation management mode of land-sea linkage.

(8) Antimicrobial textile derived from cellulose

In the aftermath of the epidemic, there has been a growing emphasis on individuals' consciousness towards personal safety. There is much concern among scientific experts on the optimal methods for efficiently inhibiting the proliferation of pathogenic germs and achieving their total eradication. Textiles serve as the primary protective barrier for the human body, with a loose and porous structure along with a substantial specific surface area. These characteristics facilitate the absorption of oil and sweat produced during human metabolism, thus creating a favorable environment for the colonization, proliferation, and propagation of microorganisms. Harmful bacteria exhibit rapid proliferation on textile surfaces, resulting in the emission of unpleasant smells and facilitating the transmission of illnesses via indirect mechanisms within certain public settings. Consequently, this phenomenon presents a significant risk to human well-being. Hence, the prioritization of developing functional textiles, particularly those that are low-carbon and ecologically sustainable, has emerged as a critical objective.

Cellulose-based materials include functional materials derived from cellulose as the primary constituent, following specific chemical or biological processes, hence exhibiting a multitude of properties. Cellulosic materials have ecological and environmental benefits, including their biodegradability and renewability. Cellulose-based antibacterial materials often include many types of fibers, such as bamboo fiber, chitosan fiber, hemp fiber, and kapok fiber. Antimicrobial textile materials represent significant potential for diverse applications within the textile industry. Notably, they may be used in the production of medical supplies, including surgical garments and medical dressings, as well as home products like towels and beds. Due to the growing environmental consciousness among individuals, there has been a notable preference for cellulose-based antibacterial textile materials by several brands and organizations. The advancement of technology will contribute to the enhanced performance and refinement of cellulose-based antibacterial textile materials, hence expanding their potential applications within the textile industry.

(9) Research on the bioaugmentation of food functional components

In recent years, nutrition and health problems have become increasingly prominent, and the health risks caused by poor diet and nutritional imbalance have ranked first among the global disease risks, seriously affecting human life and health, and restricting the orderly development of society and economy. Using bioaugmentation technology to increase the content of important functional components in food is an important way to reduce and prevent malnutrition and micronutrient deficiencies prevalent in developing countries. Improving the micronutrient content in crops that can be absorbed and utilized by the human body through breeding techniques is an important means of bioaugmentation. Major crops such as rice, wheat, maize and sweet potato, which is enriched with micronutrients such as iron, zinc and vitamin A, have been successfully cultivated and will transit from farmland to dining tables, greatly improving the nutritional deficiencies of the poor. In addition, selenium is an essential trace element for human body, and 29% of China's areas are severely selenium deficient. The bioaugmentation of selenium-rich crops relies on the inheritance and genetic engineering technology based on modern molecular biotechnology, and the more effective way is to improve the added value of agricultural products and promote the high-quality development of selenium-rich industry through agronomic management technology based on soil selenium fertilizer and foliar selenium application. Compared with crop bioaugmentation, food bioaugmentation can solve micronutrient deficiency in the short term and can accurately target nutrient deficient populations. Unsaturated fatty acids such as DHA and EPA are crucial for fetal brain development, but the body's own synthesis is very limited. The content of DHA in ruminant milk and the nutritional value of dairy products were improved by oral intake of algae or fucoxanthin as feed additives. Systematically sorting out the invention patents in the field of bioaugmentation of food functional components will be conducive to evaluating the degree of technological development of this industry, indicating the future development direction of this field, and providing a practical reference for the implementation of precision nutrition strategies and the improvement of national health.

(10) Cell factory technology for sustainable production of lactic acid from lignocellulose

Lactic acid is a biocompatible organic carboxylic acid with a wide range of applications in the fields of pharmaceutical, food and cosmetic, etc. The production methods of lactic acid mainly include chemical synthesis and biosynthesis. Due to the advantages of environmental friendliness and low production cost, the biosynthesis method is gradually replacing the conventional chemical synthesis method. However, biosynthesis usually employs fermentation production of cassava starch and other food crops to obtain lactic acid, which has led to social controversy over food and fuel issues. Therefore, bulk lactic acid chemicals still suffer from oversupply. Lignocellulose, a second-generation biomass substrate, is a non-edible renewable resource. In this case, lignocellulose as a raw material for the biosynthesis of lactic acid can effectively solve the above social issues. However, the structure and components of lignocellulose are relatively complex, and most of them are carried out by batch fermentation in the production of lactic acid. This inevitably causes long fermentation time, low yield, and easy generation of impurities. Cell factory technology can be used to produce target products through biosynthetic pathways by engineering reconfiguration of complex living organisms. In terms of both industrial application and economics, the use of cell plant technology is an effective way to achieve sustainable production of lactic acid bulk chemicals from lignocellulose. In the future, there is still a need for further research and development of raw material pretreatment and biodetoxification processes accompanying the cell factory technology for sustainable lactic acid production from lignocellulose, as well as further improvement of the production efficiency of the biosynthesis stage, so as to realize the continuity of the whole process of lactic acid production.

2.2 Interpretations for three key engineering development fronts

2.2.1 Low-carbon source wastewater denitrification technology

In the face of the increasing global production of reactive nitrogen, establishing a "low-nitrogen society" has become an essential measure to control environmental pollution and maintain the health of ecosystems. Continuously raising standards for nitrogen discharge in wastewater is an enduring theme in the global water treatment industry. However, urban wastewater treatment plants often face a shortage of carbon sources, making it challenging for traditional denitrification processes to achieve the desired treatment results. Against the backdrop of the world's move towards dual carbon goals (the goal of reaching peak carbon emissions before 2030 and achieving carbon neutrality before 2060), the development of low-carbon source wastewater denitrification technologies is a crucial pathway to achieving green water treatment processes.

To meet the demand for low-carbon source wastewater denitrification, researchers have developed several innovative denitrification processes, each with distinct characteristics.

1) Sulfur-based autotrophic denitrification: This technology utilizes sulfur and other inorganic compounds as electron donors. It eliminates the need for adding organic carbon sources, making it compatible with existing treatment processes. It has already found application in some wastewater treatment plants.

2) Shortcut nitrification-denitrification: In this process, nitrification is controlled to primarily occur at the nitrite phase. This reduces the requirement for carbon sources, lowers energy consumption during the reaction, reduces the reactor's footprint, and ultimately lowers treatment costs.

3) Simultaneous nitrification-denitrification: This process achieves both nitrification and denitrification simultaneously under conditions of low dissolved oxygen. This approach offers advantages such as shortened reaction times, reduced reactor volume, and decreased consumption of organic carbon sources.

4) Anaerobic ammonia oxidation (anammox): Anammox processes use ammonia as an electron donor to reduce nitrite under anaerobic or anoxic conditions. This results in the production of nitrogen gas without the need for carbon sources, making it an economically and technically feasible option. These innovative denitrification processes provide various solutions for addressing nitrate pollution while minimizing the carbon footprint and treatment costs.

By combining multiple processes, it's possible to optimize denitrification under low-carbon source conditions. For instance, the combination of shortcut nitrification and anammox theoretically allows for denitrification in wastewater without the need for carbon sources. This technology has been widely applied in high-concentration ammonia wastewater with limited carbon sources, such as leachate, dyeing wastewater, and anaerobic digestion supernatant. However, applying the shortcut nitrification-Anammox process to municipal mainstream sewage still faces significant challenges, and there are no stable, long-term practical applications yet.

In an international context, China leads in the number of core patent related to "low-carbon source wastewater denitrification technology", accounting for 98.51% of the total (Table 2.2.1). China has absolute advantages in quantity over other countries. While France and the USA have fewer patent publications than China, their patents tend to receive more citations on average. This suggests that China's research and innovation in low-carbon source wastewater denitrification technology are on the rise in terms of quantity but require further enhancement in terms of influence and originality.

Among the institutions contributing to core patents in "low-carbon source wastewater denitrification technology", the Top 10 are all based in China (Table 2.2.2). Beijing University of Technology ranks first with 92 core patents, and the citations per patent is relatively high at 6.37. While commercial companies like China Petroleum & Chemical Corporation and Beijing Enterprises Water Group (China) Investment Company Limited have also contributed to core patent output, there is room for further enhancing their influence. It's worth noting that there is currently no collaboration among these organizations in the field of low-carbon source wastewater denitrification technology. In the future, it is essential to move beyond a purely quantitative approach, emphasizing assessments that measure the quality and impact of research output. This approach can encourage research institutions to focus on the quality and influence of their work, promote collaboration between universities and businesses, and foster the sustainable growth of this field.

Looking ahead to the future trends in wastewater denitrification technology, it should be grounded in the fundamental principles of autotrophic biological denitrification and technological development. Researchers should explore the coupling of Anammox with other denitrification processes. Additionally, efforts should be focused on the development of new aeration systems and intelligent precise control technologies. This will help address challenges in controlling shortcut nitrification and Anammox under low-temperature and low-ammonia-nitrogen conditions, reduce greenhouse gas emissions during the process, and further achieve efficient total nitrogen removal in urban sewage (Figure 2.2.1).

Table 2.2.1 Countries with the greatest output of core patents on "low-carbon source wastewater denitrification technology"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	927	98.51	2 543	86.70	2.74
2	France	4	0.43	226	7.71	56.50
3	Republic of Korea	4	0.43	8	0.27	2.00
4	USA	2	0.21	102	3.48	51.00
5	Austria	2	0.21	0	0.00	0.00
6	Japan	1	0.11	32	1.09	32.00
7	Netherlands	1	0.11	22	0.75	22.00

Table 2.2.2 Institutions with the greatest output of core patents on "low-carbon source wastewater denitrification technology"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Beijing University of Technology	92	9.78	586	19.98	6.37
2	Harbin Institute of Technology	15	1.59	47	1.60	3.13
3	China Petroleum & Chemical Corporation	15	1.59	15	0.51	1.00
4	Tongji University	14	1.49	42	1.43	3.00
5	Beijing Enterprises Water Group (China) Investment Company Limited	13	1.38	54	1.84	4.15
6	Anhui Jianzhu University	13	1.38	33	1.13	2.54
7	Hohai University	12	1.28	18	0.61	1.50
8	Institute of Hydrobiology Chinese Academy of Sciences	11	1.17	75	2.56	6.82
9	Chongqing University	11	1.17	8	0.27	0.73
10	Nanjing University	10	1.06	96	3.27	9.60

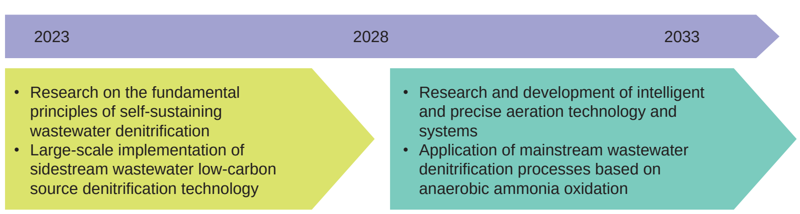

Figure 2.2.1 Roadmap of the engineering development front of "low-carbon source wastewater denitrification technology"

2.2.2 Laser detection technology of bio-optical profile in upper ocean water

The laser detection technology of marine water profile is an emerging technology that emits one or more beams of laser from the laser to the seawater, and the detection system receives the echo signal emitted by the marine water target after being excited by the laser, and then collects and analyzes the signal data through the computer system to obtain the bio-optical profile of the upper water body of the ocean. It is the only remote sensing technology that could obtain the information of the layered marine biogeochemical profile. The existing marine remote sensing technology is generally two-dimensional plane remote sensing, which has a huge gap with the detection requirements of water profile structure required by marine business and scientific applications. Marine lidar can promote the detection ability of existing marine remote sensing from two-dimensional to three-dimensional. Its application scope involves bio-optics, ecology, marine dynamics, target detection, etc., and has great potential in marine observation. Ocean laser remote sensing is a new generation of "probe" for ocean remote sensing. It provides a new three-dimensional observation method for national space security, resource development and dual-carbon strategy. It is an international frontier in the field of ocean remote sensing and an important part of the three-dimensional ocean monitoring system. It is of urgent national demand and important scientific significance to carry out research on laser detection technology of bio-optical profile of upper ocean water.

In recent years, both domestically and internationally, the development of systems and technologies related to the fluorescence and profile parameters of substances in seawater has mainly focused on the detection needs of marine biogeochemical profiles. Most of these systems and technologies are mainly ship borne, and research on the principles and mechanisms of large-scale three-dimensional detection in airborne and even spaceborne environments is still being carried out, which is in the stage of key technological breakthroughs. In terms of detection principles, the focus is on meter scattering or fluorescence detection, and there is relatively little research on hyperspectral resolution lidars with higher detection accuracy. In terms of inversion algorithms and applications, there is relatively little research on the challenges of multiple scattering by LiDAR and active passive optical closure, and scientific applications are still in the early stages. The technology of satellite-based ocean profile detection has not yet broken through, and there is currently no specialized LiDAR satellite for ocean profile detection internationally.

At present, the main research directions and development trends include: ① developing new system lidar systems such as blue-green multi wavelength, hyperspectral resolution, and single photon in ocean profiles, breaking through key technologies such as seawater hyperspectral resolution detection, narrow linewidth high-power blue light sources, and instantaneous large dynamic range and high sensitivity detection; ② developing a new multimodal three-dimensional radiation transfer simulation technology for lidar coupled with complex marine environments and remote sensors, forming an industry recognized and widely available commercial lidar multiple scattering simulation software tool; ③ developing high-precision lidar ocean optical and biological parameter profile inversion, active passive fusion, and authenticity verification technologies, breaking through key challenges such as multiple scattering correction, active passive optical parameter closure, active passive spatial fusion, and spectral fusion; ④ developing the application technology of ocean laser in cutting-edge science, ecological environment, and carbon cycle fields, promoting the process of China's ocean profile detection LiDAR satellite from scientific experiments to commercialization.

Among the main countries with the greatest output of core patents on "laser detection technology of bio-optical profile in upper ocean water" (Table 2.2.3), China ranks first in terms of published patents and second in terms of citations; the USA ranks second in terms of published patents and first in terms of citations. The total number of published patents in China and the USA accounts for approximately 67.52%. According to Figure 2.2.2, there is a lack of cooperation among other countries except for the USA and Germany. In terms of the main output institutions (Table 2.2.4), the top ten institutions with published patents are mainly concentrated in China and the USA. There is a lack of cooperation among various institutions. In a word, although China and the USA are in a dominant position in this field, the cooperation between countries is still relatively lacking. It is necessary to strengthen the cooperation between China and other countries and strengthen the international influence and greater voice of research in this field. Figure 2.2.3 shows the roadmap of the engineering development front of "laser detection technology of bio-optical profile in upper ocean water".

Table 2.2.3 Countries with the greatest output of core papers on "laser detection technology of bio-optical profile in upper ocean water"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	193	44.78	364	26.13	1.89
2	USA	98	22.74	454	32.59	4.63
3	Japan	44	10.21	63	4.52	1.43
4	Germany	38	8.82	86	6.17	2.26
5	Republic of Korea	12	2.78	11	0.79	0.92
6	Russia	6	1.39	1	0.07	0.17
7	Canada	5	1.16	24	1.72	4.80
8	India	4	0.93	4	0.29	1.00
9	Italy	4	0.93	4	0.29	1.00
10	Switzerland	4	0.93	2	0.14	0.50

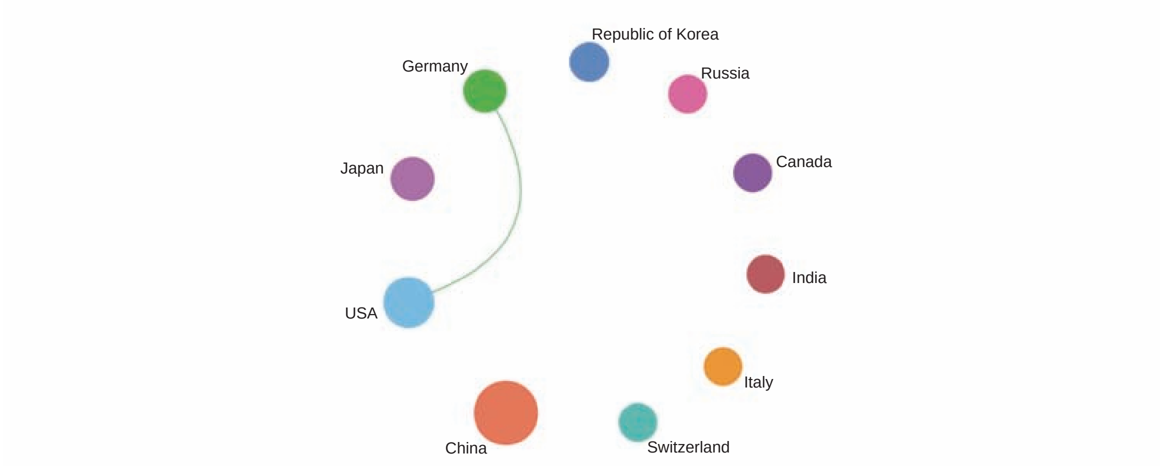

Figure 2.2.2 Collaboration network among major countries in the engineering development front of "laser detection technology of bio-optical profile in upper ocean water"

Table 2.2.4 Institutions with the greatest output of core patents on "laser detection technology of bio-optical profile in upper ocean water"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	AMADA Holdings Company Limited	12	2.78	24	1.72	2.00
2	Jilin University	11	2.55	34	2.44	3.09
3	University of Rochester	6	1.39	44	3.16	7.33
4	Beijing University of Technology	6	1.39	18	1.29	3.00
5	Beijing Institute of Technology	6	1.39	14	1.01	2.33
6	Daimler AG	6	1.39	11	0.79	1.83
7	Xi'an Jiaotong University	5	1.16	10	0.72	2.00
8	Fudan University	4	0.93	18	1.29	4.50
9	IPG Photonics Corporation	4	0.93	17	1.22	4.25
10	University of California	4	0.93	12	0.86	3.00

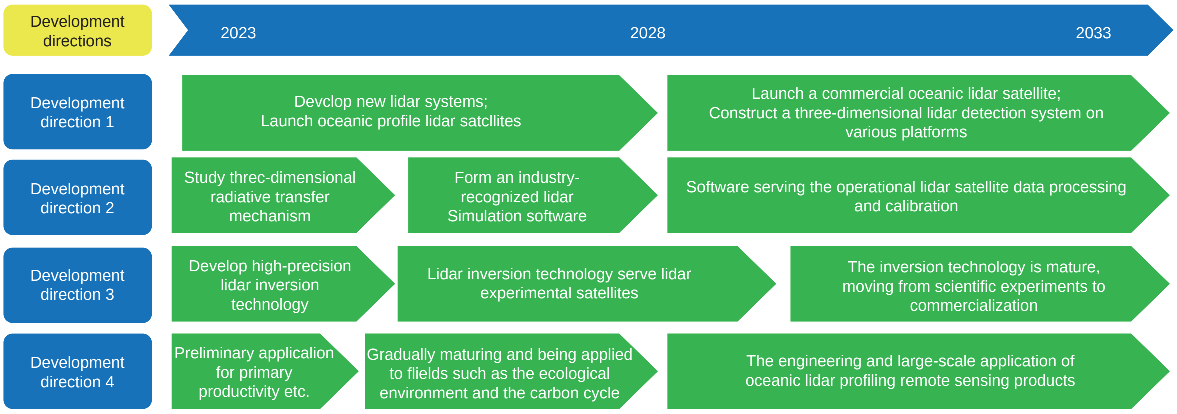

Figure 2.2.3 Roadmap of the engineering development front of “laser detection technology of bio-optical profile in upper ocean water”

2.2.3 Antimicrobial textile derived from cellulose

As individuals experience an increase in their level of living and a heightened knowledge of health and hygiene, they place more emphasis on the preservation of personal safety and well-being. Antibacterial textile materials have the capacity to inhibit the growth of bacteria and fungi, hence safeguarding the materials against contamination and fiber deterioration. Furthermore, these materials play a crucial role in impeding the transmission of illnesses. Hence, the development of antibacterial functional materials, the production of antibacterial functional products, and the investigation of high-performance sterilizing and virus-killing medical and protective materials, with a specific focus on environmentally sustainable and renewable cellulose-based antibacterial textile materials, assume significant importance. This necessitates the implementation of innovative strategies and the advancement of developmental initiatives. In recent years, China has consistently emerged as a leading global investor in research and development pertaining to cellulose-based antibacterial textile materials. Moreover, China’s ongoing efforts in advancing the technology associated with cellulose-based antibacterial textile materials have shown a continuous drive for innovation.

According to the data shown in Table 2.2.5, China has disclosed a total of 722 core patents in recent years, representing 72.20% of the overall number of publicly declared patents. The USA and Germany followed with 69 and 44 published patents respectively. The quantity of technological patents pertaining to cellulose-based antibacterial textile materials in China surpasses that of industrialized nations such as the USA, Germany, and Japan. Nevertheless, according to the data shown in Table 2.2.5, China’s patents just exhibit a citations per patent of 1.39, which is much lower than that of industrialized nations such as the USA, Germany, and Japan. Cellulose-based antibacterial textile materials are still less original in technology, lacking in innovation and influence. As indicated by the data presented in Table 2.2.6, among the main institutions in terms of patent production, Jiangnan University in China holds the highest position. However, its patents exhibit relatively low citation frequency and average citations. Figures 2.2.4 and 2.2.5 depict the collaborative network among major countries and institutions within this particular domain. The level of collaboration and research partnership among institutions or firms in this developmental front is notably deficient. The only entities that have established cooperative contacts are University of North Carolina at Chapel Hill and Entregrion Incoporated Corporation. It is worth noting that the degree of industrialization in this context is rather low. The potential for collaboration between production, education, and research in the development of cellulose-based antibacterial textile materials technology remains significant. It is imperative to intensify international exchanges and collaborations with foreign countries and institutions. Additionally, it is crucial to augment China’s innovation capacity in this domain. Moreover, there is a need to amplify the assessment of the impact of scientific research output to incentivize research institutions to prioritize the quality and influence of their research. Furthermore, it is essential to foster the integration of academic institutions and enterprises and facilitate the expeditious advancement of specific disciplines.

Table 2.2.5 Countries with the greatest output of core patents on "antimicrobial textile derived from cellulose"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	722	72.20	1 002	25.43	1.39
2	USA	69	6.90	1 917	48.64	27.78
3	Germany	44	4.40	177	4.49	4.02
4	Japan	26	2.60	58	1.47	2.23
5	Republic of Korea	22	2.20	2	0.05	0.09
6	Israel	20	2.00	131	3.32	6.55
7	Sweden	11	1.10	109	2.77	9.91
8	Canada	11	1.10	71	1.80	6.45
9	Austria	10	1.00	35	0.89	3.50
10	India	10	1.00	1	0.03	0.10

Table 2.2.6 Institutions with the greatest output of core patents on "antimicrobial textile derived from cellulose"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Jiangnan University	20	2.00	25	0.63	1.25
2	Argaman Technologies Company Limited	17	1.70	152	3.86	8.94
3	Entegrion Incoporated	13	1.30	1 160	29.43	89.23
4	University of North Carolina at Chapel Hill	13	1.30	1 160	29.43	89.23
5	Luolai Life Science and Technology Company Limited	11	1.10	20	0.51	1.82
6	OrganoClick AB	10	1.00	105	2.66	10.50
7	Lenzing AG	10	1.00	35	0.89	3.50
8	Qingdao Niximi Biotechnology Company Limited	10	1.00	11	0.28	1.10
9	Badische Anilin-und-Soda-Fabrik (BASF)	9	0.90	146	3.70	16.22
10	Nippon Paper Industries Company Limited	9	0.90	17	0.43	1.89

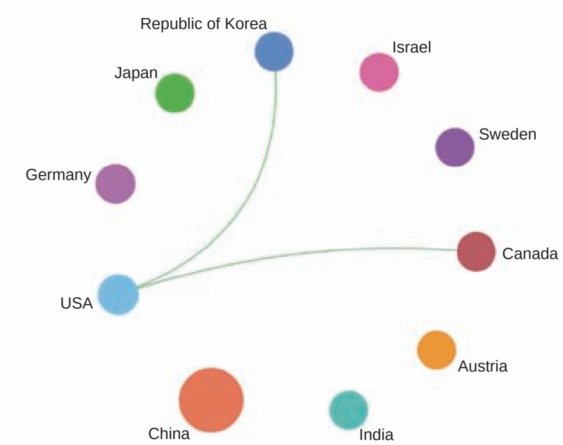

Figure 2.2.4 Collaboration network among major countries in the engineering development front of "antimicrobial textile derived from cellulose"

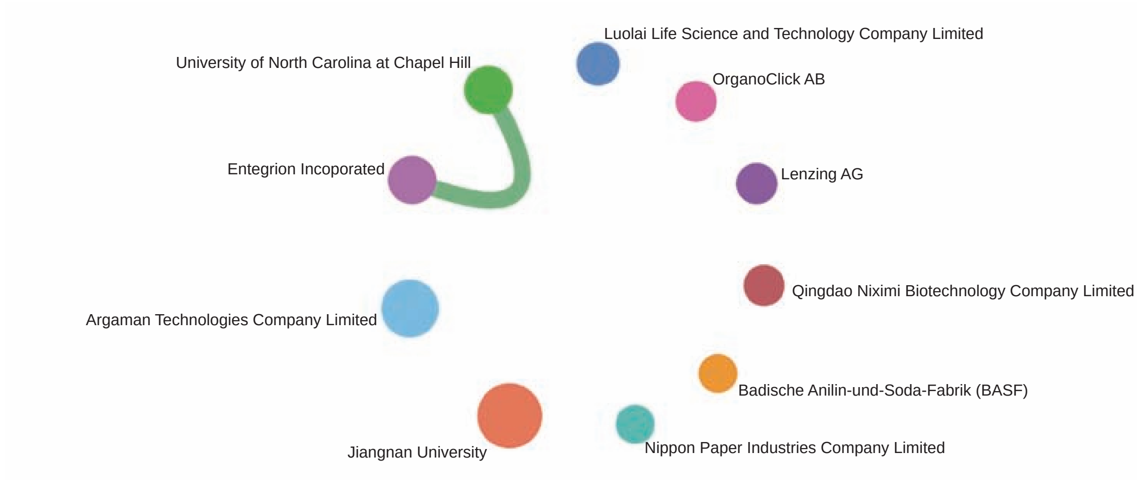

Figure 2.2.5 Collaboration network among major institutions in the engineering development front of “antimicrobial textile derived from cellulose”

In recent years, the emergence of microbial pollution and various bacterial maladies has had a significant impact on human health and safety, resulting in a greater concern for health and higher requirements for antimicrobial materials. High-molecular-weight cellulose is the most prevalent biodegradable material and renewable energy source in nature. It is primarily comprised of glucose linked by β-(1,4)-glycosidic bonds. It features a large specific surface area, effective water absorption, stable chemical properties, biodegradability, and outstanding biocompatibility. The creation of cellulose materials with superior antibacterial properties has become a prominent area of study.

Currently, cellulose-based antimicrobial materials consist of two components: matrix cellulose or derivatives of cellulose and antimicrobial agents. There are plant cellulose matrix, bacterial cellulose matrix, and ascidian cellulose matrix present in the cellulose matrix. Inorganic antimicrobial agents, organic synthetic antimicrobial agents, and natural antimicrobial agents are examples of antimicrobial agents. Methods for preparing cellulose-based antibacterial materials mainly include: ① directly preparing antimicrobial textiles from natural antibacterial cellulose fibers, which have general durability in terms of antibacterial performance; ② preparing antimicrobial fibers by spinning the antimicrobial agent into fibers and then processing the fibers into products. The co-blending method has certain limitations in selecting the antimicrobial agent, which requires thermal stability and good compatibility with polymer resins; the composite spinning method uses less antimicrobial agent than the co-blending method, combined with the special structure of the prepared fibers, the product’s resistance to water washing is better, but its manufacturing process is more complex and its production cost is relatively higher; and ③ the antibacterial material is obtained by finishing the matrix cellulose with antibacterial agent. Currently, this technique is the industry standard for producing antimicrobial textiles. There are various preparation techniques, such as immersion, surface coating, resin finishing, surface grafting modification, and microencapsulation, based on the method of preparation. These approaches are simple to process and have effective antibacterial properties.

The primary research directions for antimicrobial materials based on cellulose include:

1) Modification of cellulose fibers: enhancing their antibacterial efficacy by modifying the fibers’ surface structure, polarity, and hydrophobicity.

2) Synthesis and addition of antimicrobial agents: synthesis of novel antimicrobial agents or addition of existing antimicrobial agents to cellulose fibers in order to accomplish antibacterial functionality.

3) Composite of cellulose fibers with other materials: producing composite materials with improved antibacterial efficacy by combining cellulose fibers with other antibacterial-functional materials.

4) Processing and production of cellulose-based antimicrobial textiles: researching the production processes and techniques of cellulose-based antimicrobial textiles in order to enhance production efficiency and product quality.

Trends in the development of antimicrobial materials based on cellulose include:

1) High-performance: the development of cellulose-based antimicrobial textile materials with enhanced antibacterial performance to increase market competitiveness;

2) Diversification: the development of a variety of types and functions of cellulose-based antimicrobial textile materials to satisfy the requirements of various sectors;

3) Environmental protection: using environmentally benign and sustainable raw materials and production procedures to create antimicrobial textile materials based on cellulose with environmental properties;

4) Individuation: developing personalized and fashionable antimicrobial textile materials based on cellulose to increase product value.

Figure 2.2.6 shows the roadmap of the engineering development front of “antimicrobial textile derived from cellulose” during a timeframe of five to ten years. It showcases the progression of cellulose-based antimicrobial textiles from the initial laboratory phase, through the engineering phase, and ultimately towards the industrialization phase.

As people continue to pursue health and quality of life, the market demand for antimicrobial textiles derived from cellulose will increase. In the future, environmental protection, health, functionality, and intelligence will play a larger role in the development of antimicrobial textiles derived from cellulose. Simultaneously, the efficacy and added value of cellulose-based antimicrobial textiles will be continuously enhanced through the continued application and development of new technologies. In the future, it is anticipated that cellulose-based antimicrobial textiles will be applied and developed in additional fields.

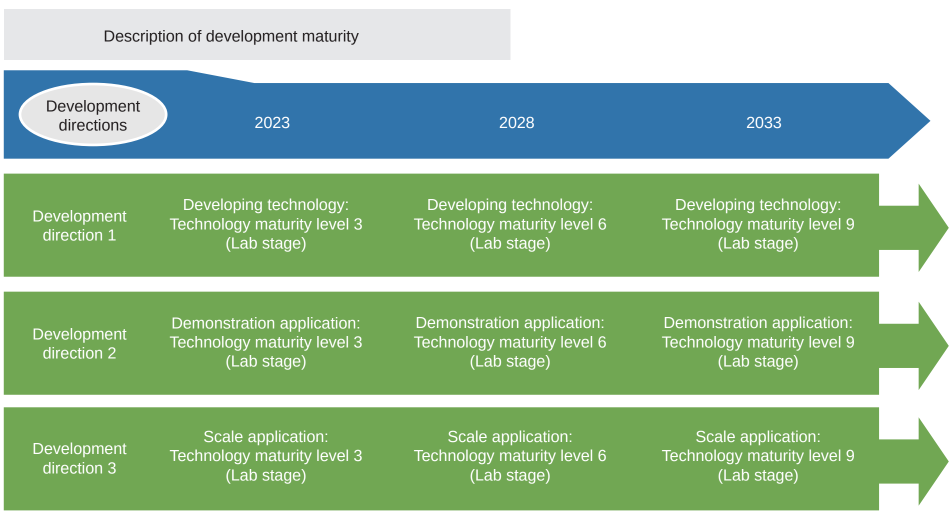

Figure 2.2.6 Roadmap of the engineering development front of “antimicrobial textile derived from cellulose”

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VII. Agriculture

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The Top 10 engineering research fronts in the field of agriculture mainly include: ① research on biological mechanisms and mechanisms related to crop breeding, such as "crop pan-genome" and "functional gene identification by multi-omics in animals"; ② research on improving the quality, yield, and green production of animal and plant products, such as "mechanisms and methods for synergistic improvement of crop yield, quality, and efficiency", "genetic basis and regulatory network for the quality formation of horticultural crops", "intelligent identification mechanism and real-time monitoring technology for crop diseases and pests", "diagnosis of forest diseases and pests based on deep learning", and "straw modification and rapid decomposition technology"; ③ animal medicine and nutrition are still at the forefront of research in animal husbandry, such as "mechanisms of host inflammatory response regulation mediated by significant animal pathogens", as well as "antibiotic-free nutritional regulation techniques for the intestinal health and growth of livestock and poultry". The number of core papers in the engineering research fronts in agriculture ranges from 18 to 67, with an average of 47 papers, similar to previous years. The citations per paper range of articles is 28.94–225.40, with an average of approximately 84.54 times. The core papers are mainly published in 2018 and 2019, with the average publication year of core papers on "intelligent identification mechanism and real time monitoring technology for crop diseases and pests", "straw modification and rapid decomposition technology", "antibiotic-free nutritional regulation techniques for the intestinal health and growth of livestock and poultry", "intelligent collaborative operation technology for multiple agricultural machinery", and "diagnosis of forest diseases and pests based on deep learning" being 2019, compared to other selected fronts, it is closer to the current situation (Tables 1.1.1 and 1.1.2).

Table 1.1.1 Top 10 engineering research fronts in agriculture

No.	Engineering research front	Core papers	Citations	Citations per paper	Mean year
1	Crop pan-genome	50	11 270	225.40	2017.7
2	Mechanisms and methods for synergistic improvement of crop yield, quality, and efficiency	43	3 684	85.67	2018.5
3	Genetic basis and regulatory network for the quality formation of horticultural crops	58	3 321	57.26	2018.6
4	Intelligent identification mechanism and real-time monitoring technology for crop diseases and pests	42	4 876	116.10	2019.2
5	Straw modification and rapid decomposition technology	67	1 939	28.94	2019.8
6	Mechanisms of host inflammatory response regulation mediated by significant animal pathogens	54	2 603	48.20	2018.3
7	Antibiotic-free nutritional regulation techniques for the intestinal health and growth of livestock and poultry	35	2 313	66.09	2019.1
8	Functional gene identification by multi-omics in animals	50	2 645	52.90	2018.2
9	Intelligent collaborative operation technology for multiple agricultural machinery	40	3 615	90.38	2019.2
10	Diagnosis of forest diseases and pests based on deep learning	18	1 340	74.44	2019.3

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in agriculture

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Crop pan-genome	4	7	9	9	3	0
2	Mechanisms and methods for synergistic improvement of crop yield, quality, and efficiency	9	16	8	6	4	0
3	Genetic basis and regulatory network for the quality formation of horticultural crops	15	13	15	12	2	1
4	Intelligent identification mechanism and real-time monitoring technology for crop diseases and pests	7	6	10	11	7	1
5	Straw modification and rapid decomposition technology	11	7	13	5	14	17
6	Mechanisms of host inflammatory response regulation mediated by significant animal pathogens	16	18	11	5	3	1
7	Antibiotic-free nutritional regulation techniques for the intestinal health and growth of livestock and poultry	0	12	11	10	1	1
8	Functional gene identification by multi-omics in animals	15	18	9	7	0	1
9	Intelligent collaborative operation technology for multiple agricultural machinery	6	9	5	13	7	0
10	Diagnosis of forest diseases and pests based on deep learning	3	3	3	5	3	1

(1) Crop pan-genome

A pan-genome is a collection of all DNA sequences of a species. In recent years, crop pan-genomics has become an essential field of the studies in crop genomics. It plays a key role in revealing the genetic variations, evolutionary histories and functional genes in crops. Currently, all the staple crops, such as maize, rice and wheat, have been assembled with multiple high-quality reference genomes. Comparing to the traditional single reference genome for a species, it has become obvious that multiple genome assemblies of different individuals or varieties will provide more adequate and accurate information in presenting the genetic diversity of the species, especially reveal the rich structure variations, such as tandem repeats, present/absent variations and chromosome translocations. Constructing pan-genome at genus level will provide valuable evidence for understanding on crop origin and evolution, decoding the domestication and de-domestication process, and revealing the evolution process of functional genes. Moreover, integrating the resourceful sequence information provides opportunity for resolving the core genes and dispensable genes at pan-genome level, promoting the mining and exploiting of beneficial gene recourses. In recent years, the achievement of super-high-quality genome assemblies, such as gap-less genome and telomere-to-telomere complete genome assemblies provide strong guidance in constructing crop pan-genome. The methodological method and analysis approaches based on pan-genomes are unceasingly improving, and the tasks such as the sequence mapping on pan-genome, functional annotation of gene family, and constructing graph-based pan-genome are calling for technical innovations. In the future, incorporating with advanced technologies, such as artificial intelligence and machine learning, and abundant phenotype data, the crop pan-genomics is expected to serve as a uniform and comprehensive coordinate system for facilitating gene mining and molecular design breeding, ultimately accelerate the crop basic research and development of improved varieties for ensuring national food security and sustainable agricultural development.

(2) Mechanisms and methods for synergistic improvement of crop yield, quality, and efficiency

The coordinated improvement of crop yield, quality and efficiency refers to the systematic revelation of the rules and mechanisms underlying the synergistic formation of high yield, superior quality, and high efficiency. This involves selecting suitable varieties and optimal planting times based on local conditions to make full use of local temperature and light resources, optimizing nutrient management and irrigation to achieve efficient utilization of fertilizer and water resources. As a result, it accomplishes the synergistic enhancement of crop yield, quality, and efficiency. At present, the yield per unit area of major crops such as rice, wheat, and corn in China has reached a relatively high level. However, with the rapid development of China's economy and society as well as the continuous improvement in people's quality of life, the modern high-quality development of agriculture poses new requirements for crop production. There is an urgent need to not only focus on increasing yield per unit area but also to effectively enhance quality and resource utilization efficiency. Therefore, it is crucial to analyze the mechanisms and explore the pathways for the coordinated improvement of crop yield, quality, and efficiency. The core scientific issues in this regard mainly include:

1) The interplay between crop growth, development, yield, quality and efficiency, the comprehensive effects of crop-environment-cultivation measures on yield and quality efficiency, and the mechanisms underlying the coordinated improvement of crop yield and quality efficiency.

2) The evaluation index system and comprehensive selection methods for crop varieties that promote coordinated improvement in yield, quality and efficiency.

3) The regulatory pathways and key technologies that can be widely applied for the coordinated improvement of crop yield, quality and efficiency. Breakthroughs in the relevant theories and technologies mentioned above will provide essential theoretical support and modern engineering solutions for China's coordinated production of high yield, superior quality, and high efficiency crops.

(3) Genetic basis and regulatory network for the quality formation of horticultural crops

As the horticultural industry develops rapidly and the total output of horticultural products increases significantly, changes in product quality, health component content, and quality and safety issues of horticultural products have received close attention. The quality of horticultural products includes factors such as appearance, nutritional quality, and flavor quality, mainly including organ size, shape, uniformity, color, storage and transport ability, various nutrient contents (sugar, acid, starch, vitamins, mineral nutrients, flavonoids, etc.), various flavor substance contents (amino acids, aromatic substances, etc.), and taste (softness, hardness, and flavor perception). The quality traits are complex. In recent years, some research has been carried out in China on fruit shape, color, nutritional quality, flavor, and the formation and regulation mechanism of bitter substances in horticultural crops. In particular, the use of genomics, transcriptomics, metabolomics, and other methods has clarified the key regulatory genes for a few metabolic substances by exploring and analyzing the metabolic genes and their regulatory genes related to horticultural product quality. There is also an increasing understanding of the molecular mechanisms and regulatory networks of important agronomic traits. However, many metabolic substances that determine the quality of horticultural products are still unclear, and there is limited research on the molecular mechanisms and metabolic regulatory mechanisms. Therefore, in the future, different levels of gene expression cascade regulatory mechanisms and their regulatory networks, as well as the interactive regulation between plant hormone signal transduction and quality formation, the coupling regulation mechanism between quality metabolism and the environment, and other research should be carried out based on the existing foundation. It aims to explore the control network and signal transduction mechanism of horticultural product quality formation, and provide a scientific basis for improving the quality and efficiency of the horticultural production.

(4) Intelligent identification mechanism and real-time monitoring technology for crop diseases and pests

In the system for the integrated pest management, control decision is the core, prediction is the basis of decision-making, and monitoring is an indispensable basis for prediction and decision-making. Nowadays, timely, rapid, and accurate monitoring technology is very important in plant disease and pest control. With the integration and development of high and new technologies such as remote sensing, radar, image technology, quantitative molecular detection technology, sensor, Internet of Things technology, big data analysis and artificial intelligence in recent years, relatively obvious progress has been made in the construction of intelligent identification, real-time monitoring and early warning technology of crop diseases and pests, which has greatly improved the timeliness and accuracy of disease and insect monitoring. The intelligent identification technology of crop diseases and pests is mainly composed of several or several modules, such as capture and lure equipment, detection or high-definition shooting equipment, real-time transmission platform, remote monitoring platform, intelligent identification and counting model or algorithm, and network client of computer or mobile phone, the monitoring of pests and diseases has been transformed from the traditional manual investigation to the integrated remote automatic real-time monitoring, identification and diagnosis of real-time collection, transmission, identification, analysis and early warning of pest and disease information. Although the accuracy or application scope of most identification and monitoring models is inevitably limited, with the further development of computer technology such as artificial intelligence and deep learning, the intelligent identification and monitoring technology of crop pests and diseases integrated with traditional methods and emerging technologies will become the main development direction of disease and pest monitoring and early warning in the future.

(5) Straw modification and rapid decomposition technology

Straw return is important for maintaining soil fertility, improving nutrient efficiency, and slowing soil acidification. However, due to the high carbon to nitrogen ratio and the complex structure of straw components, direct straw return is not easy to decompose quickly, which may cause nitrogen deficiency, aggravate the diseases, and influence the growth of the next crop. Ectopic decomposition of straw also takes at least 2 months. Therefore, how to promote the rapid decomposition of straws is one of the urgent treatment problems in current agriculture. The process of straw decomposition to organic matter was influenced by the nature of the straw itself, soil chemical and soil microbial properties. Straw modification refers to the exogenous addition of nitrogen fertilizers, nanomaterials, chemical modifiers, enzyme preparations or microbial inoculants, and so on, which can regulate the physical, chemical, biological processes during the straw decomposition, and thus improve the decomposition efficiency of straw and product efficacy. With the rapid development of techniques such as microbiology and organic substance characterization, it can be achieved to increase the speed of in-situ or ectopic straw decomposition, improve the performance of organic products and nutrient capacity based on techniques of highly efficient microbial inoculant and straw modification, and finally establish regional precision technology for rapid decomposition of straw under different climatic environments. This is of great significance for realizing the sustainable and low-carbon development of agriculture, and accelerating the agricultural recycling economy.

(6) Mechanisms of host inflammatory response regulation mediated by significant animal pathogens

As China is the world's largest consumer of livestock and poultry and animal-derived food, the prevention and control of significant animal diseases are crucial for the healthy development of animal husbandry and public health security. The invasion of animal pathogens induces the host immune response, and the regulation of host inflammatory response is closely related to the occurrence and development of diseases. Inflammatory response is a self-defense mechanism of the host against stimuli, playing an important role in pathogen clearance, enhancing disease resistance, and preventing the spread of pathogens. Specifically, upon invading the host, pathogens are recognized by host pattern recognition receptors, initiating a series of intracellular signal transduction, recruiting a large number of chemokines, cytokines, and activated immune cells to gather at the infected site to clear the pathogens, causing local inflammatory reactions. Inflammatory response is mediated by pro-inflammatory cytokines, and some important pathogens can induce a large release of pro-inflammatory cytokines to cause "cytokine storm", leading to strong local inflammation of tissues and assisting pathogen proliferation; meanwhile, pathogens can cause macrophage lysis by activating the inflammasome, resulting in the escape and spread of pathogens. In addition, pathogens can inhibit the expression and release of pro-inflammatory factor by regulating various signaling pathways in host cells, thereby avoiding clearance by the host and establishing persistent infection. Elaborating the key mechanisms by which pathogens regulate host inflammatory response is crucial for understanding the pathogenicity of pathogens and seeking new treatment of infectious diseases. The relevant research results will also provide important guidance and theoretical basis for vaccine development and the prevention and control of significant animal diseases.

(7) Antibiotic-free nutritional regulation techniques for the intestinal health and growth of livestock and poultry

The problems of antibiotic resistance, ecological environment pollution and food safety caused by the abuse of antibiotics have seriously affected the healthy development of animal husbandry in China. In 2020, China issued a “prohibition order” to completely prohibit the addition of growth-promoting antibiotics in feed, which brings great challenges to intestinal health and growth and development of livestock and poultry. Based on this, the development and application of green and safe non-resistant nutrition control technology to maintain the intestinal health of livestock and poultry and promote their growth and development is an inevitable trend of efficient and sustainable development of animal husbandry in China. The non-resistant nutrition regulation technology is based on the balance of feed “nutrient structure”, integrating integrated nutrients to the comprehensive nutritional regulation of animal immunity, intestinal health and pathogenic factors, so as to promote the intestinal development of animals under the condition of non-resistance, improve the body’s resistance to disease, and ensure animal health and efficient production. The key of non-resistant nutrition technology system lies in the balance and optimization of feed nutrient structure, feed processing modulation and precise feeding, regulating intestinal microecological balance from the aspects of nutrient source selection, formula design and optimization, additive combination screening, feed processing modulation, feeding methods and fecal bacteria transplantation, so as to promote intestinal health and efficient growth of livestock and poultry. It is difficult and hot to further strengthen the basic theoretical research of non-resistant nutrition and promote the application of non-resistant nutrition regulation technology system. The relevant research results will certainly provide theoretical guidance and technical support for the intestinal health and efficient growth of livestock and poultry under non-resistant conditions.

(8) Functional gene identification by multi-omics in animals

Functional gene identification by multi-omics in animals is a process that involves the comprehensive analysis of various genetic, transcriptomic, and proteomic data, along with related bioinformatics methods, to identify and study genes in the animal genome that have important functions and biological significance. The process of functional gene identification in animal multi-omics typically includes the following steps: data collection, data preprocessing, bioinformatics analysis (which involves the application of bioinformatics tools and algorithms to analyze the preprocessed data, including genome assembly, gene localization, gene function annotation, transcriptome assembly, expression analysis, protein identification and quantification), functional gene mining (which involves the identification of genes with important functions and biological significance by combining the analysis results with existing biological knowledge, and may include enrichment analysis, differential expression analysis, protein-protein interaction network analysis, etc.), functional annotation and interpretation, and biological validation (which includes experimental validation or further functional studies to confirm the important roles of functional genes in biological processes). This technique aims to decipher the molecular genetic basis of important traits such as meat quality and quantity, milk production and quality, wool production and quality, egg production, as well as growth, development, reproduction, disease resistance, heat stress resistance, and low-oxygen tolerance in superior animal breeds. It provides a basis for the theory and technological innovation of genome-guided breeding, greatly improves the accuracy of selecting and creating superior traits such as high yield, good quality, disease resistance, and stress tolerance in agricultural animals, and accelerates the process of targeted breeding of improved varieties.

(9) Intelligent collaborative operation technology for multiple agricultural machinery

According to statistics, the global population is projected to reach 9.7 billion by 2050, with a growth in food demand exceeding 70%. Labor shortages have become a pressing issue in agricultural production, necessitating the advancement of agricultural modernization and industrial upgrading. Unmanned intelligent agricultural machinery, through automation technology, can operate autonomously to reduce reliance on manual labor and achieve high-efficiency agricultural operations, thereby enhancing production efficiency. However, as agricultural modernization progresses, the expansion of farmland continues, and achieving intelligent and unmanned operation for a single agricultural machine may not suffice to meet the demands of large-scale, efficient production. The realization of intelligent collaborative operations among multiple agricultural machines has become a research focal point. This includes communication and networking technologies facilitating real-time data transmission and information exchange between machines, technologies for perceiving and identifying real-time agricultural environmental conditions and crop growth statuses, autonomous planning and coordinated control technologies for multiple agricultural machines, task coordination and operation scheduling technologies among these machines, safety and security technologies for both single and multiple agricultural machine collaborative operations—covering aspects such as safe maneuvering, data security, system reliability, and fault diagnosis, among others. Breaking through the core key technologies related to these aspects will enable task specialization and collaboration in agricultural production, leading to improved operational efficiency and supporting the development of smart agricultural applications.

(10) Diagnosis of forest diseases and pests based on deep learning

Deep learning-based approaches for forest pest and disease diagnostics represent an innovative strategy for detecting and monitoring these threats in woodland environments. Deep learning, a subset of machine learning techniques, centers on constructing and training multi-layered neural networks to autonomously glean features and patterns from extensive datasets. Such methods excel in accurately recognizing pests and diseases and scrutinizing their prevalence trends by synergizing data. This approach offers several advantages over conventional methods of identification, including alleviating the repetitive tasks undertaken by professionals, conserving labor, providing timely insights, and delivering high levels of precision and efficiency. Current research in the realm of forest pest and disease diagnosis utilizing deep learning encompasses various dimensions. These encompass image recognition for identifying forest pests and diseases, tracking pest populations and their dynamics via the detection of light- or pheromone-induced responses. Furthermore, this approach extends to monitoring alterations in the prevalence of forest pests and diseases and predicting their trajectory using high-resolution imagery from satellites and unmanned aerial vehicles. These images encompass visible, multispectral, and hyperspectral data. As artificial intelligence technology continues to advance, constructing a comprehensive model for forest pests and diseases, delving into data fusion and multimodal information, exploring model design, compression, and automated architecture searches are imperative. These measures collectively enhance the efficiency and adaptability of the model. Predicting pest and disease occurrences based on regional monitoring networks is pivotal in adapting to contemporary environmental shifts and combating the invasion of pests and diseases. This is particularly vital for ensuring the sustainable development of forestry under prevailing mega-trends.

1.2 Interpretations for three key engineering research fronts

1.2.1 Genetic basis and regulatory network for the quality formation of horticultural crops

With the rapid development of the horticulture industry and the substantial increase in total production of horticultural crops, there has been a growing concern for changes in product quality characteristics, content of health-promoting compounds, and the safety of horticultural products. Horticultural product quality includes aspects such as appearance, nutritional quality, and flavor quality, which mainly involve organ size, shape, uniformity, color, shelf-life, content of various nutrients (sugar, acid, starch, vitamins, mineral nutrients, flavonoids, etc.), content of various flavor compounds (amino acids, aromatic substances, etc.), and sensory attributes (texture, mouthfeel, etc.). The characteristics of product quality are complex. In recent years, China has conducted research on fruit shape, color, nutritional quality, flavor, and the formation and regulation mechanisms of bitter compounds in horticultural crops. Particularly, methods such as genomics, transcriptomics, and metabolomics have been applied to identify and analyze genes related to the metabolism of substances affecting horticultural product quality. This research has shed light on the key regulatory genes for a small number of metabolites and has led to a better understanding of the molecular mechanisms and regulatory networks underlying important agronomic traits. However, the molecular mechanisms and metabolic regulation of most metabolites that determine horticultural product quality remain unclear, with limited research in this area.

With the rapid development of sequencing technology and the quick decrease in costs, the genomes of many horticultural plants have been sequenced, or updated to more high-quality genomes. Chinese scientists have made outstanding contributions in this field. According to incomplete statistics, genome sequencing has been completed for more than 50 horticultural crops, providing a foundation for breeding new and superior crop varieties through molecular design methods.

Currently, over 60 quantitative trait loci controlling sugar content have been identified. Additionally, proteins indirectly involved in sugar metabolism, such as sucrose transporters, starch synthesis enzymes, and vacuole processing enzymes, have been analyzed. The team led by YE Zhibiao successfully identified major-effect locus TFM6 (tomato fruit malate 6), an Al-activated malate transporter ALMT9, that regulates malate accumulation in tomatoes through association analysis (mGWAS). They confirmed that WRKY42 negatively regulates ALMT9 expression by binding to the W-box on the ALMT9 promoter, thereby inhibiting malate accumulation in tomato fruits. It has been reported that 237 loci in tomatoes are associated with enzyme-catalyzed reactions in the ascorbic acid metabolic pathway, and the metabolic network of genes and corresponding enzymes related to the ascorbic acid metabolic pathway has been preliminarily established.

Many genes involved in carotenoid biosynthesis pathways have been isolated, cloned, and functionally validated. Secondary metabolites such as flavonoids, alkaloids, phenylpropanoids, and aromatic compounds are also important components in the formation of nutritional and flavor quality in horticultural crops. In this field, China's Institute of Agricultural Sciences and the University of Florida in the USA have collaborated to identify 33 key flavor compounds influencing consumer preferences. They have also discovered 49 key loci regulating the accumulation of flavor compounds, revealing the material basis and genetic improvement path of tomato flavor. This provides feasible breeding solutions for cultivating delicious tomatoes.

Due to the complexity of quality traits, research on the genetic basis and regulatory networks underlying trait formation is still in its early stages. The future focus of research will be on the application of molecular biology techniques to establish and optimize genetic transformation systems for horticultural crops, to uncover key genes related to crop quality, to elucidate the regulatory role of these genes in quality, and to establish a more precise molecular regulatory network by identifying important nodal regulatory genes. Efforts will be made to break the unfavorable gene linkage with quality traits, achieve simultaneous improvements in horticultural crop quality and other desirable traits such as stress resistance, and breed high-quality horticultural crop varieties. The mechanisms by which environmental factors and cultivation techniques regulate quality will be explored, and key technologies for quality horticultural crop cultivation in controlled environments will be established.

In the front of "genetic basis and regulatory network for the quality formation of horticultural crops", the top three countries in terms of the publication of core papers (Table 1.2.1) are China (63.79%), the USA (27.59%), and Italy (12.07%). The citations per paper in this front is distributed from 46.25 to 93.67, of which the citations per paper of Israel and the USA exceeds 70.00. In terms of the distribution of research institutions (Table 1.2.2), Chinese Academy of Sciences (CAS), Anhui Agricultural University (AAU), and Chinese Academy of Agricultural Sciences (CAAS) have produced many core papers and cited many times. Cooperation among countries is more common, and cooperation among China and the USA is relatively closer (Figure 1.2.1). The output is mainly in the cooperation network among institutions (Figure 1.2.2), and there are certain cooperation relations among these institutions. The main output countries of the citing papers are China and the USA, with China accounting for 49.05% and the USA accounting for 14.35% (Table 1.2.3). In terms of the main output institutions of the citing papers (Table 1.2.4), CAS, CAAS, and Nanjing Agricultural University (NAU) ranked among the top three in the number of citing papers. Figure 1.2.3 shows the roadmap of the engineering research front of "genetic basis and regulatory network for the quality formation of horticultural crops".

Table 1.2.1 Countries with the greatest output of core papers on "genetic basis and regulatory network for the quality formation of horticultural crops"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	37	63.79	2 288	61.84	2018.7
2	USA	16	27.59	1 178	73.62	2019.1
3	Italy	7	12.07	423	60.43	2017.7
4	UK	7	12.07	367	52.43	2019.1
5	Israel	6	10.34	562	93.67	2018.2
6	Spain	6	10.34	281	46.83	2018.5
7	France	6	10.34	279	46.50	2018.5
8	Netherlands	5	8.62	261	52.20	2019.2
9	Austria	4	6.90	185	46.25	2018.0
10	Germany	3	5.17	160	53.33	2018.7

Table 1.2.2 Institutions with the greatest output of core papers on "genetic basis and regulatory network for the quality formation of horticultural crops"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Chinese Academy of Sciences	6	10.34	384	64.00	2019.7
2	Anhui Agricultural University	6	10.34	302	50.33	2018.7
3	Chinese Academy of Agricultural Sciences	5	8.62	280	56.00	2020.0
4	Huazhong Agricultural University	4	6.90	342	85.50	2017.5
5	Zhejiang University	4	6.90	329	82.25	2018.8
6	University of California, Davis	4	6.90	251	62.75	2019.2
7	Edmund Machinery Foundation Research and Innovation Center	4	6.90	218	54.50	2017.8
8	South China Agricultural University	4	6.90	190	47.50	2018.8
9	Cornell University	3	5.17	387	129.00	2018.3
10	United States Department of Agriculture Agricultural Research Service	3	5.17	266	88.67	2019.3

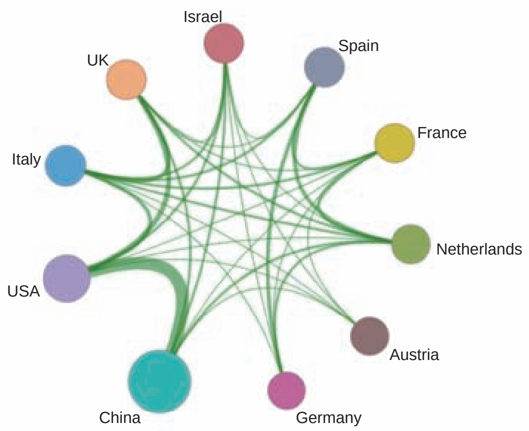

Figure 1.2.1 Collaboration network among major countries in the engineering research front of "genetic basis and regulatory network for the quality formation of horticultural crops"

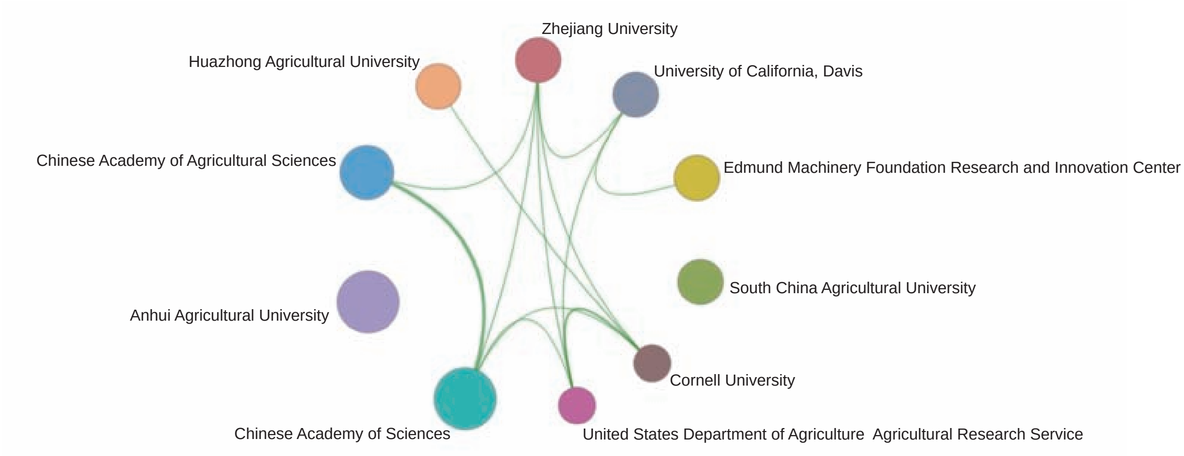

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of "genetic basis and regulatory network for the quality formation of horticultural crops"

Table 1.2.3 Countries with the greatest output of citing papers on "genetic basis and regulatory network for the quality formation of horticultural crops"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	1 623	49.05	2021.1
2	USA	475	14.35	2020.8
3	Italy	216	6.53	2020.7
4	Spain	174	5.26	2020.8
5	Germany	161	4.87	2020.9
6	India	155	4.68	2021.2
7	France	154	4.65	2020.5
8	Britain	110	3.32	2021.0
9	Australia	84	2.54	2020.5
10	Japan	79	2.39	2020.8

Table 1.2.4 Institutions with the greatest output of citing papers on "genetic basis and regulatory network for the quality formation of horticultural crops"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	150	15.59	2021.1
2	Chinese Academy of Agricultural Sciences	141	14.66	2021.1
3	Nanjing Agricultural University	100	10.40	2021.0
4	South China Agricultural University	92	9.56	2021.0
5	Huazhong Agricultural University	90	9.36	2020.9
6	Zhejiang University	73	7.59	2021.1
7	Fujian Agriculture and Forestry University	70	7.28	2021.1
8	Anhui Agricultural University	70	7.28	2020.8
9	United States Department of Agriculture Agricultural Research Service	62	6.44	2020.8
10	Shandong Agricultural University	57	5.93	2021.2

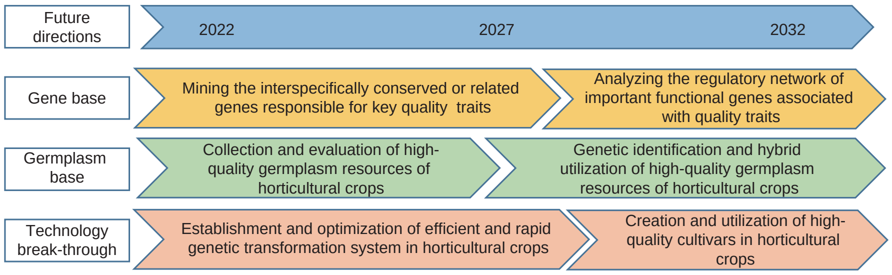

Figure 1.2.3 Roadmap of the engineering research front of "genetic basis and regulatory network for the quality formation of horticultural crops"

1.2.2 Functional gene identification by multi-omics in animals

The healthy development of the livestock and poultry industry is a strategic necessity to ensure the safety of our country's grain and livestock products. As a key component of the breeding industry, the seed industry will further contribute to the development of animal husbandry in the future. The molecular mechanisms underlying important economic traits in livestock and poultry are extremely complex. Currently, the incomplete annotation of functional genomic maps and the unclear understanding of key genes and regulatory mechanisms for excellent traits severely restrict the efficient utilization of germplasm resources, genetic improvement, and the creation of new breeds in livestock and poultry.

With the continuous development of modern biotechnology, livestock and poultry breeders have progressed from macroscopically describing the genetic laws of traits based on genetic power to analyzing the regulatory regions that influence quantitative traits using molecular markers, and now to directly deciphering the relationship between DNA sequence variations and complex traits. These known causative mutations of important traits can be directly applied to breeding practices, laying a solid foundation for the cultivation of superior breeds. Functional gene mining in animal multi-omics is crucial for deciphering the molecular genetic basis of important economic traits in livestock and poultry, as well as for genome sequencing and functional genomics research. It is also an important prerequisite for the development of superior animal breeds and has been a focus of research in the field of animal genetic breeding both domestically and internationally for a long time.

Since 2009, whole-genome selection technology based on genome-wide SNP chips has rapidly developed and been widely used in dairy cattle, beef cattle, pigs, and broilers breeding in developed countries in Europe and America. In 2014, Australian scientists initiated the international 1 000 Bull Genomes Project. In 2015, the European Union and the USA established the "International Animal Genomic Functional Annotation Project" to predict the important traits of livestock and poultry germplasm resources. Chinese scientists have led or participated in genome projects of different livestock and poultry species such as chickens, ducks, pigs, geese, yaks, and sheep. They have also jointly launched scientific programs like the Ten Thousand Bird Genomes Project and the Macro-genome Project with different countries, laying a foundation for elucidating the genetic mechanisms of important economic traits. In addition, domestic and foreign researchers have identified a group of differentially expressed genes, differentially expressed proteins, and differentially methylated genes related to important economic traits such as growth, meat quality, reproduction, and milk production. They have explored the regulatory relationships between them and made important discoveries in molecular mechanisms such as pig carcass traits, milk composition synthesis and mastitis resistance in dairy cows, and the development of Cashmere goat hair follicles. They have obtained whole-genome copy number variation maps for cattle, pigs, beef cattle, chickens, and ducks, and discovered multiple candidate genes related to milk production traits, body size traits, carcass traits, immune traits, and meat quality traits. The initiation of domestic and international animal genomic functional annotation projects (FAANG, FarmGTEx, etc.) has led to the elucidation of the molecular regulatory mechanisms of agricultural animal phenotypic traits in the era of genomics. Meanwhile, as functional gene mining in animal multi-omics continues to deepen in basic research applications, agricultural animal breeding is accelerating its transition from traditional conventional breeding to multi-omics intelligent design breeding.

Animal multi-omics functional gene mining technology mainly includes comprehensive analysis of big data in animal pan-genomics, genomics, epigenomics, spatiotemporal transcriptomics, proteomics, metabolomics, and phenomics. It integrates methods from genetics, genomics, bioinformatics, molecular biology, biochemistry, cell biology, and animal breeding to reveal panoramic multi-dimensional omics features of animals. It aims to identify genetic loci and molecular markers (QTL) related to traits such as high productivity, high quality, stress resistance, and disease resistance in animals. It explores key genetic variations, functional genes, regulatory sequences, and regulatory networks, revealing the interactions between genes, phenotypes, and the environment. It provides molecular genetic selection markers and manipulation targets for animal breeding. This technology aims to decipher the molecular genetic basis of important traits such as meat quantity and quality, milk yield and dairy quality, fur yield and quality, egg production, as well as growth, development, reproduction, disease resistance, heat stress tolerance, and other important traits in excellent animal germplasm. It provides a basis for genome-guided precision breeding theory and technological innovation, greatly improving the accuracy of selecting and creating high-yielding, high-quality, disease-resistant, and stress-tolerant traits in agricultural animals, and accelerating the targeted breeding process of superior breeds.

In terms of core papers published in the front of “functional gene identification by multi-omics in animals”, the top three countries are the USA (38.00%), China (38.00%), and the UK (10.00%) (Table 1.2.5). The citations per paper of this front ranges from 45.00 to 82.00, with the UK, Australia, and the Netherlands are all more than 65.00. In terms of the main output institutions, University of California, Davis, University of Toulouse, and Northwest A & F University produce core papers with higher citations per paper (Table 1.2.6). As shown in Figure 1.2.4, research cooperation between countries is relatively common, with the cooperation between the UK, the USA, and China being relatively closer. As shown in Figure 1.2.5, there is a certain degree of cooperation among main institutions. The top two countries in the number of citing papers are China and the USA, with China accounting for 30.38% and the USA accounting for 24.14%, and the mean year is relatively late, demonstrating strong research and development momentum (Table 1.2.7). In terms of the main institutions of citing papers (Table 1.2.8), CAS, CAAS, and China Agricultural University rank top three,

Table 1.2.5 Countries with the greatest output of core papers on “functional gene identification by multi-omics in animals”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	19	38.00	1 153	60.68	2018.6
2	China	19	38.00	924	48.63	2018.4
3	UK	5	10.00	348	69.60	2018.6
4	France	5	10.00	287	57.40	2018.0
5	Germany	5	10.00	225	45.00	2018.4
6	Australia	4	8.00	288	72.00	2018.5
7	Canada	4	8.00	235	58.75	2017.8
8	Denmark	3	6.00	168	56.00	2018.0
9	Spain	3	6.00	167	55.67	2018.0
10	Netherlands	2	4.00	164	82.00	2018.5

Table 1.2.6 Institutions with the greatest output of core papers on “functional gene identification by multi-omics in animals ”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	University of California, Davis	4	8.00	270	67.50	2018.5
2	University of Toulouse	4	8.00	252	63.00	2018.2
3	Northwest A & F University	4	8.00	190	47.50	2018.0
4	The University of Queensland	3	6.00	232	77.33	2018.3
5	University of Edinburgh	3	6.00	224	74.67	2018.7
6	Iowa State University	3	6.00	205	68.33	2020.0
7	United States Department of Agriculture Agricultural Research Service	3	6.00	190	63.33	2019.0
8	Aarhus University	3	6.00	168	56.00	2018.0
9	National Research Institute for Agriculture, Food and the Environment	3	6.00	163	54.33	2017.7
10	China Agricultural University	3	6.00	159	53.00	2019.3

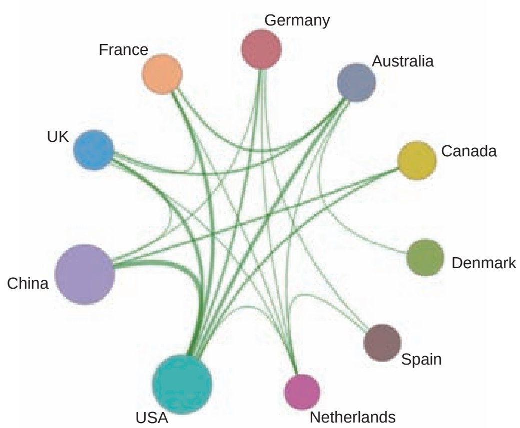

Figure 1.2.4 Collaboration network among major countries in the engineering research front of “functional gene identification by multi-omics in animals”

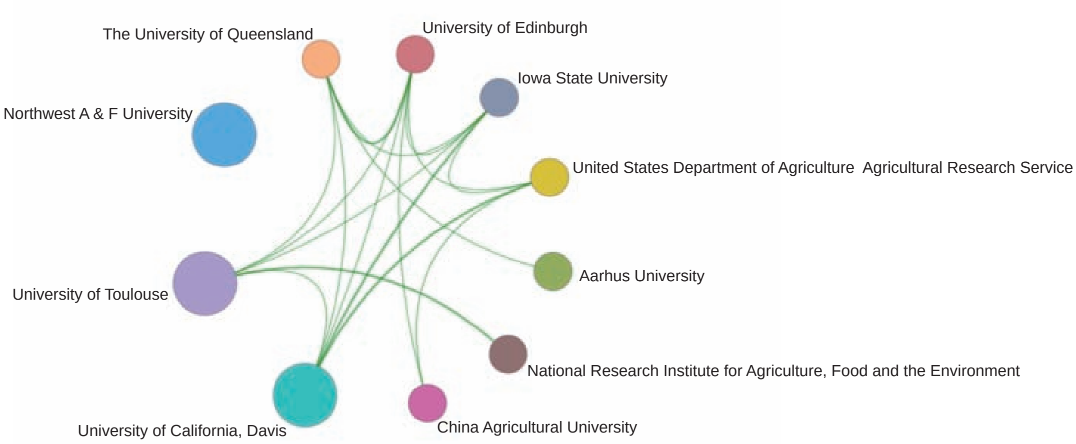

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of “functional gene identification by multi-omics in animals”

Table 1.2.7 Countries with the greatest output of citing papers on "functional gene identification by multi-omics in animals"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	979	30.38	2021.0
2	USA	778	24.14	2020.5
3	UK	247	7.66	2020.5
4	Germany	235	7.29	2020.3
5	France	177	5.49	2020.5
6	Australia	172	5.34	2020.6
7	Canada	145	4.50	2020.5
8	India	144	4.47	2020.9
9	Italy	127	3.94	2020.4
10	Spain	123	3.82	2020.5

Table 1.2.8 Institutions with the greatest output of citing papers on "functional gene identification by multi-omics in animals"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	104	14.05	2021.1
2	Chinese Academy of Agricultural Sciences	102	13.78	2020.9
3	China Agricultural University	86	11.62	2020.7
4	University of Edinburgh	81	10.95	2020.7
5	United States Department of Agriculture Agricultural Research Service	75	10.14	2020.7
6	Northwest A & F University	59	7.97	2020.7
7	Huazhong Agricultural University	56	7.57	2021.1
8	The University of Queensland	52	7.03	2020.4
9	Sichuan Agricultural University	47	6.35	2020.7
10	University of California, Davis	40	5.41	2020.5

with the number of citing papers of CAS ranking first.

It is worth noting that complex economic traits in animals are governed by a large number of genetic components, which are exhibited through intricate developmental regulatory networks and gradually shaped by natural or artificial selection. The contribution of a single gene to a trait is limited, and its effect can vary significantly under different environmental conditions. The regulatory networks that involve coupling and antagonism between different traits, as well as their underlying core regulatory units, have not been fully deciphered. The phenomena of multiple effects caused by genetic linkage and one effect caused by multiple factors have become key bottlenecks in animal multi-omics functional gene mining. These bottlenecks also limit molecular design breeding in animals, especially the genetic progress in multi-trait coordinated improvement. Therefore, future research directions should focus on two aspects: enriching the sources of multi-omics data and expanding the depth of multi-omics integrated analysis. ① Traditional functional genomics studies that focus on static genetic associations for single traits (such as SNP and GWAS), or functional studies of individual genes or signaling pathways during development, have difficulty accurately depicting the systemic evolutionary framework from genotype to phenotype. To address the unique multi-factor regulatory models underlying different economic traits, emerging integrated analysis technologies such as three-dimensional genomics (Hi-C), protein interaction networks, multi-dimensional epigenomics (ATAC-Seq, ChIP-seq), single-cell sequencing, spatial transcriptomics, gene editing techniques, and optimized GWAS algorithms can be fully utilized. These technologies can help unravel the regulatory networks formed by the combination and interaction of different alleles at different loci, which contribute to the formation of complex trait phenotypes. Key functional elements that can be used in breeding practices can be discovered. ② Molecular genetic studies of important traits in agricultural animals require the support of large-scale experimental populations and data, as well as continuous, systematic, and in-depth monitoring and research on key phenotypes. Therefore, the extensive research on multi-omics intelligent design breeding inevitably leads to an exponential growth of multi-omics information in animals. Interpreting massive and heterogeneous multi-omics data and integrating multi-omics information from different studies to analyze the relationship between genetic variations and important economic traits present significant challenges. Overcoming the bottleneck of single-omics analysis limited to "correlation" between markers and phenotypes and breaking through the difficulties in revealing "causality" can be achieved through reference to animal multi-omics databases and dynamic integrated analysis methods. From an integrative and systems biology perspective, the genetic basis of complex traits in animals can be elucidated. Figure 1.2.6 shows the roadmap of the engineering research front of "functional gene identification by multi-omics in animals".

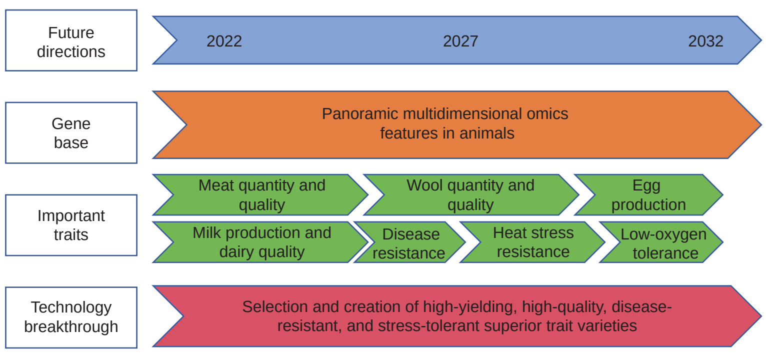

Figure 1.2.6 Roadmap of the engineering research front of "functional gene identification by multi-omics in animals"

1.2.3 Diagnosis of forest diseases and pests based on deep learning

Forests, as intricate non-rigid organic entities within nature, play a pivotal role in ecosystems by shaping ecological niches, facilitating energy flow, and orchestrating material cycling. Furthermore, they stand as vital carbon sinks, harboring one of the largest repositories of organic carbon within terrestrial ecosystems. A report from the United Nations' Food and Agriculture Organization (FAO) indicated that in 2020, global forest coverage spanned 4.045 billion hectares, constituting 31% of the Earth's land area. Pairing this with insights from China's comprehensive forest resources assessments and statistical data, the calculation of average forest benefits reveals that China's per-unit forest area annually retains 192.34 tons of water, absorbs 12.1 kilograms of airborne pollutants, and releases 315 kilograms of oxygen. However, challenges persist, particularly concerning the health of forest ecosystems. In 2022, China encountered substantial threats from forestry pests, with 178 million mu (approximately 11.87 million hectares) of forest land imperiled by major pests. Pine wood nematode disease affected 22 million mu (approximately 1.47 million hectares) of forest land, resulting in 10 million diseased and dead pine trees. Additional threats, such as the white moth, imperiled another 28 million mu (approximately 1.87 million hectares). Consequently, research into diagnosing forest tree diseases and pests holds immense significance for upholding ecosystem health, enhancing forestry productivity, and safeguarding biodiversity.

Traditional methods of pest and disease identification in forests rely on manual techniques and conventional image processing methods. These approaches often suffer from limitations related to human judgment, constrained feature extraction capabilities, and compromised accuracy and efficiency. A scarcity of skilled technicians further exacerbates these issues, leading to substantial economic losses caused by delayed prevention and control efforts or excessive intervention that impacts ecological security and biodiversity.

Deep learning-based methods, on the other hand, capitalize on constructing intricate neural networks to autonomously grasp complex features and patterns from extensive datasets, resulting in more precise and rapid pest and disease diagnoses. These methods encompass a spectrum of algorithms, including multi-task learning for versatile diagnosis, transfer learning to minimize data requirements and training time, target detection algorithms to pinpoint pest and disease locations, and semantic segmentation to precisely delineate infected and healthy areas. Ongoing research within the domain of deep learning-based forest pest and disease diagnostics centers on several key facets. These include bolstering model efficiency and generalization, enabling real-time monitoring and feedback, enhancing automation and intelligence, leveraging data fusion and multimodal information, and harnessing the potential of AI's large-scale models. This approach chiefly concentrates on areas such as forest pest and disease image recognition, population dynamics monitoring through techniques like lamp lure or pheromone-induced pest counting, trend monitoring in forest pest and disease areas using satellite imagery and unmanned aerial vehicle data (encompassing visible, multispectral, and hyperspectral information), and the prediction of pest and disease occurrence trends.

In the front of "diagnosis of forest diseases and pests based on deep learning", the three leading countries in terms of the number of core papers published (Table 1.2.9) are the USA, China, and India. The citations per paper of this front ranges from 45.00 to 123.00, with the exceptions of Egypt and India, which exhibit a citation frequency surpassing 50.00. In terms of research institution distribution (Table 1.2.10), institutions such as COMSATS University Islamabad, Prince Sultan University, University of Washington, University of Hawaii, and University of Hawaii at Manoa have demonstrated a high output of core papers along with a high citations per paper. The primary countries contributing to the citing papers include China, India, and the USA (Table 1.2.11). Regarding the main institutions of citing papers (Table 1.2.12), CAS, COMSATS University Islamabad, and Deakin University hold prominent positions in terms of the number of citing papers. Collaboration between countries is extensive and interconnected (Figure 1.2.7), with relatively close collaborations observed between Egypt, India, and Saudi Arabia. As for the collaborative network among the main institutions (Figure 1.2.8), there exists a degree of cooperation both within institutions of the same country and across institutions in different countries. For instance, notable collaboration exists between Seoul National University and University of Waterloo, University of Hawaii and University of Hawaii at Manoa, and University of Washington, Prince Sultan University, and

Table 1.2.9 Countries with the greatest output of core papers on "diagnosis of forest diseases and pests based on deep learning"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper/%	Mean year
1	USA	5	27.78	436	87.20	2019.4
2	China	5	27.78	263	52.60	2019.4
3	India	4	22.22	196	49.00	2020.2
4	Saudi Arabia	3	16.67	249	83.00	2021.0
5	Pakistan	2	11.11	219	109.50	2020.0
6	Australia	2	11.11	124	62.00	2019.0
7	Brazil	2	11.11	105	52.50	2020.0
8	Egypt	2	11.11	90	45.00	2020.0
9	Canada	1	5.56	123	123.00	2017.0
10	Republic of Korea	1	5.56	123	123.00	2017.0

Table 1.2.10 Institutions with the greatest output of core papers on "diagnosis of forest diseases and pests based on deep learning"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper/%	Mean year
1	China University of Mining and Technology (Beijing)	2	11.11	122	61.00	2019.5
2	COMSATS University Islamabad	1	5.56	150	150.00	2020.0
3	Prince Sultan University	1	5.56	150	150.00	2020.0
4	University of Washington	1	5.56	150	150.00	2020.0
5	University of Hawaii	1	5.56	131	131.00	2018.0
6	University of Hawaii at Manoa	1	5.56	131	131.00	2018.0
7	Seoul National University	1	5.56	123	123.00	2017.0
8	University of Waterloo	1	5.56	123	123.00	2017.0
9	Yonsei University	1	5.56	123	123.00	2017.0
10	Emory University	1	5.56	123	123.00	2021.0

Table 1.2.11 Countries with the greatest output of citing papers on "diagnosis of forest diseases and pests based on deep learning"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	395	28.66	2021.2
2	India	217	15.75	2021.5
3	USA	215	15.60	2020.9
4	Saudi Arabia	109	7.91	2021.5
5	UK	78	5.66	2021.1
6	Republic of Korea	77	5.59	2021.1
7	Pakistan	76	5.52	2021.4
8	Australia	62	4.50	2020.7
9	Italy	55	3.99	2020.9
10	Spain	47	3.41	2021.4

Table 1.2.12 Institutions with the greatest output of citing papers on "diagnosis of forest diseases and pests based on deep learning"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Chinese Academy of Sciences	34	17.62	2021.4
2	COMSATS University Islamabad	25	12.95	2021.3
3	Deakin University	17	8.81	2019.3
4	Prince Sultan University	16	8.29	2021.0
5	Northwestern Polytechnic University	16	8.29	2021.1
6	University of Washington	15	7.77	2021.9
7	Noroff University College	14	7.25	2021.9
8	King Abdullah University of Science & Technology	14	7.25	2021.9
9	King Saud University	14	7.25	2021.8
10	Central South University	14	7.25	2021.4

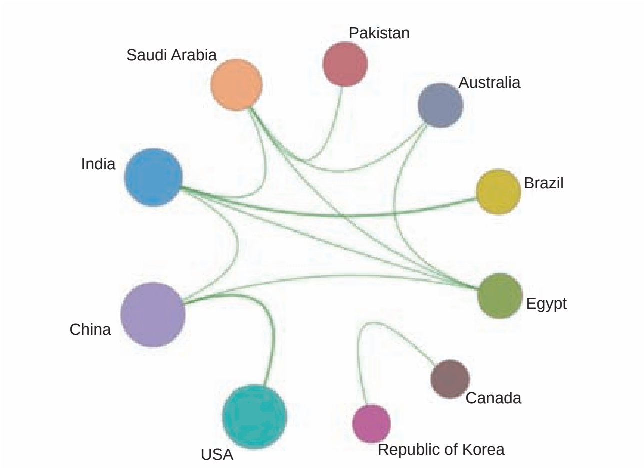

Figure 1.2.7 Collaboration network among major countries in the engineering research front of “diagnosis of forest diseases and pests based on deep learning”

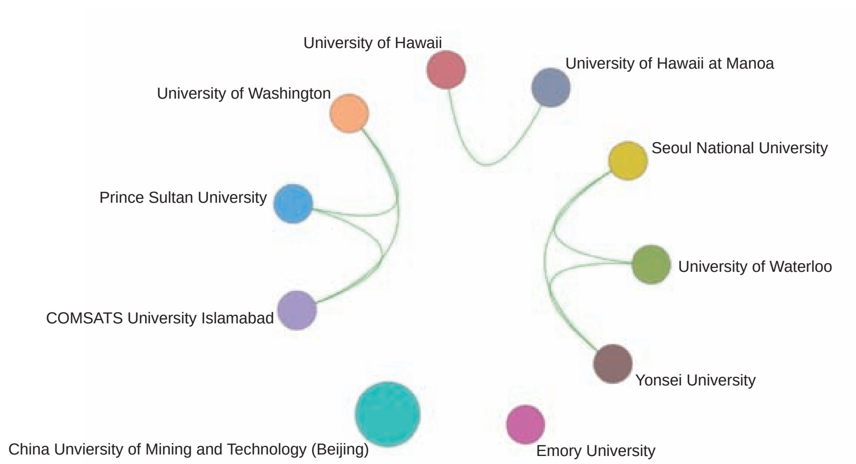

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “diagnosis of forest diseases and pests based on deep learning”

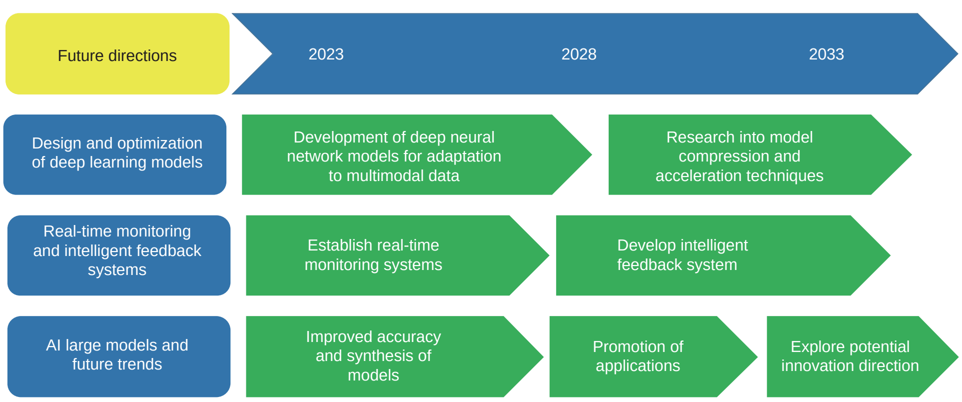

Figure 1.2.9 Roadmap of the engineering research front of “diagnosis of forest diseases and pests based on deep learning”

COMSATS University Islamabad. Figure 1.2.9 shows the roadmap of the engineering research front of “diagnosis of forest diseases and pests based on deep learning”.

2 Engineering development fronts

2.1 Trends in Top 11 engineering development fronts

The Top 11 engineering development fronts in the agricultural field mainly involves directions such as agricultural green development, smart agriculture, and agricultural engineering, and reflects interdisciplinary applications (Table 2.1.1). Among them, the engineering development fronts related to agricultural green development include “crop green super-high-yield cultivation technology”, “development and utilization of high-quality germplasm resources for horticultural crops”, “molecular design of green pesticides based on structural biology”, “synergistic technology for efficient conversion of organic matter and reduction of pollutants during composting”, and “bio-refinery of wood waste”. At the same time, the in-depth application of gene editing technology is a hot research topic for researchers, such as “key technologies for unmanned farms” and “ecological breeding technology of aquatic animals”. The disclosure of core patents related to various cutting-edge technologies from 2017 to 2022 is shown in Table 2.1.2. Among them, the citations per patent of “molecular design of green pesticides based on structural biology” is as high as 19.61, indicating that agricultural green development has received widespread attention from researchers in recent years. The core patents for “development and application of genome editors in crops” have the highest number of disclosures, with 4 658 published patents (up to 1 292 in 2022) and 63 027 citations, far higher than other development fronts. The core patents for “creation of novel and efficient animal vaccines” are the least, and there were no core patents in 2022.

(1) Development and application of genome editors in crops

Genome editing refers to the genetic manipulation technology of precise insertion, deletion or replacement of DNA. Through precise editing of functional genes or regulatory sequences in organisms, genome editing technology is able to repair target genes, strengthen beneficial genes, eliminate harmful genes, and ultimately achieve the purpose of improving the function of organisms. As the most subversive and leading cutting-edge technology of biological breeding, genome editing technology has become the priority in developed countries and multinational seed companies, and is the competition commanding height in the field of global agricultural biotechnology. Using genome editing technology, Chinese scientists have realized the genetic improvement

Table 2.1.1 Top 11 engineering development fronts in agriculture

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Development and application of genome editors in crops	4 658	63 027	13.53	2020.3
2	Crop green super-high-yield cultivation technology	181	437	2.41	2019.7
3	Development and utilization of high-quality germplasm resources for horticultural crops	88	137	1.56	2020.3
4	Molecular design of green pesticides based on structural biology	111	2 177	19.61	2018.8
5	Synergistic technology for efficient conversion of organic matter and reduction of pollutants during composting	797	6 983	8.76	2018.9
6	Creation of novel and efficient animal vaccines	52	119	2.29	2019.0
7	Preparation of feed by pre-digestion fermentation bioprocessing	73	76	1.04	2019.3
8	Genomic mating breeding technology for livestock and poultry	856	1 587	1.85	2020.0
9	Key technologies for unmanned farms	1 000	3 541	3.54	2019.7
10	Bio-refinery of wood waste	46	71	1.54	2019.5
11	Ecological breeding technology of aquatic animals	52	25	0.48	2020.6

Table 2.1.2 Annual number of core patents published for the Top 11 engineering development fronts in agriculture

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Development and application of genome editors in crops	281	455	695	807	1 128	1 292
2	Crop green super-high-yield cultivation technology	20	24	43	23	39	32
3	Development and utilization of high-quality germplasm resources for horticultural crops	10	10	7	7	26	28
4	Molecular design of green pesticides based on structural biology	36	18	20	14	11	12
5	Synergistic technology for efficient conversion of organic matter and reduction of pollutants during composting	176	183	187	125	65	61
6	Creation of novel and efficient animal vaccines	6	17	9	12	8	0
7	Preparation of feed by pre-digestion fermentation bioprocessing	0	23	21	15	9	5
8	Genomic mating breeding technology for livestock and poultry	85	106	142	138	205	180
9	Key technologies for unmanned farms	127	171	144	167	219	172
10	Bio-refinery of wood waste	9	10	6	2	7	12
11	Ecological breeding technology of aquatic animals	5	1	3	5	25	13

of important agronomic traits and created new elite germplasms in a variety of crops. However, since the original core patents of genome editing nucleases are monopolized by a few foreign countries such as the USA (Cas9 and Cas12a, etc.), the industrial application of genome editing products of crops in China faces the potential risk of being controlled by others. Therefore, breaking the patent monopoly of genome editing technology, discovering new genome editing nucleases with China's independent intellectual property rights, and developing corresponding genome editing systems such as gene knockout, base editing, DNA fragment insertion and replacement in crops are of great significance for ensuring the safety of genome editing technology industry in China.

(2) Crop green super-high-yield cultivation technolgy

Crop green super-high-yield cultivation refers to the cultivation engineering technology pattern that steadily and reliably achieves the ecological and environmental friendliness of fields, the efficient utilization of resources, the high quality of crops, and the yield per unit area that can be reproduced or break through the top level in the region. With high demand for agricultural products in China and few resources such as arable land per capita, the search for higher crop yields on limited arable land is undoubtedly a basic orientation that fits the national situation. Over the long term, China's field crops in the cultivation of super-high yield has been explored in various aspects, has emerged more high-yield paradigm, creating a number of super-high yield records. However, it has focused on the breakthrough of single yield in the past, and insufficient attention has been paid to the carbon sequestration and emission reduction of the full amount of straw returned to the field, and the green and efficient use of fertilizers and water chemicals in practice. Research on the super-high yield, high-quality and high-efficiency synergistic formation of the regulation and mechanism is also lacking, the formation of super-high-yield cultivation technology is poorly stabilized, and it is difficult to replicate and popularize it in large-area operation. Therefore, in the coming times, China is in more urgent need to improve the self-sufficiency rate of agricultural products, for the above problems, in-depth study of field crops green super-yield regulation and technology, to accelerate the improvement of the self-sufficiency rate of agricultural products is particularly important. The key scientific problems include: ① the formation pattern of green ultra-high yield of field crops and the mechanism and regulation pathway of expanding reservoirs and strong sources of steady flow; ② green super-high yield planting methods and new patterns of cultivation; ③ soil carbon sequestration and fertilization techniques for full quantity and pollution-free return of super-high yielding straw to the field; ④ mechanism and technology of green and efficient utilization of fertilizer and water chemicals under super-high yield condition; and ⑤ integration and replicable demonstration of regionalized green super-high yield mechanical cultivation technology. With independent innovation in crop cultivation and cross-fertilization with physiology, environmental ecology, informatics, mechanical engineering and other cutting-edge sciences, new theories and technologies of green and super-high-yield cultivation of crops with Chinese characteristics will be created to achieve synergistic breakthroughs in yield, quality, productivity and to increase more than 30% of production efficiency of field crops, and the comprehensive production capacity of crops, effectively promoting the modernization of China's crop production.

(3) Development and utilization of high-quality germplasm resources for horticultural crops

Horticultural germplasm resources refer to the collective name of horticultural plants carrying different germplasm, including cultivated varieties (variations, cultivars, and types) of various horticultural crops, wild species, wild and semi-wild relatives, as well as artificially created varieties or lines, or genetic materials. Horticultural germplasm resources are the material foundation for the exploration and innovation of high-quality germplasm, genetic breeding of horticultural crops, and the development of the industry. China, as the origin of numerous horticultural crops, possesses abundant horticultural germplasm resources. However, there is still insufficient work in utilizing and developing these resources, especially in terms of high-quality resources. The core technological needs include: ① collection, evaluation, and utilization of high-quality germplasm resources of horticultural crops, establishing a high-quality horticultural crop germplasm resource bank; ② innovation and application of multi-trait, high-throughput, and precision phenotypic identification technologies for horticultural crops; ③ exploration and application of high-quality relevant genes in wild germplasm resources, functional analysis of important genes for quality, and regulation networks; and ④ creation of high-quality germplasm resources in horticultural crops through sexual hybridization, physical and chemical mutagenesis, genetic engineering, and other methods. Breaking through these related technologies will greatly promote the breeding of high-quality horticultural crops in China.

(4) Molecular design of green pesticides based on structural biology

The conventional approach to pesticide development involves generating a vast array of lead compounds from diverse chemical precursors, followed by direct organism testing and iterative design-synthesis-test-analysis cycles to optimize their efficacy, ultimately leading to the discovery of novel pesticides. According to statistics, the successful development of a new pesticide necessitates the synthesis of 140 000 compounds over a span exceeding 10 years, requiring an investment of nearly 300 million USD. Unfortunately, research and development costs and cycles are continuing to rise. To address these challenges, the molecular design of pesticides based on three-dimensional structural information of molecular targets has emerged as the prevailing approach in novel green pesticide development. Molecular design of green pesticides based on structural biology involves two main technical directions. Firstly, acquiring the three-dimensional structural information of the target and understanding the interaction between the target molecule and the active small molecule are essential prerequisites for molecular design. By analyzing the structural characteristics of the target active sites, elucidating the key motifs involved in small molecule binding, and discerning the structural disparities of the targets among different species, it can provide a foundation for efficient and specific design of green pesticides. In recent years, with the rapid advancement of structural biology technologies such as cryo-electron microscopy, an increasing number of pesticide molecular targets have been obtained, such as chitin synthase and nicotinic receptor. However, the available pesticide molecular target structures are still scarce, and further research is warranted. Second, the utilization of structure-based molecular design techniques is crucial in expediting the research and development cycle. The process of molecular design necessitates a comprehensive consideration of various key aspects, including virtual screening of initial compounds, optimization from initial to lead compounds, druggability analysis of compounds, prediction of physicochemical and toxicological properties, selection of candidate compounds, and other crucial steps. Establishing a structure-based molecular design system and platform for developing green pesticides is essential to facilitate these steps.

(5) Synergistic technology for efficient conversion of organic matter and reduction of pollutants during composting

The term "efficient conversion of organic matter and reduction of pollutants during composting" describes the process of converting organic matter into stable humus. This is achieved through the use of functional microorganisms, which work under specific conditions of moisture, material ratio, and oxygen concentration. The process is manually controlled to promote humification and reduce emissions of greenhouse gases, odors, and other pollutants caused by the mineralization of composting.

The core technology include:

1) Screen microorganisms that can both degrade lignocellulose and synthesize humus. Research and develop composite microbial agents that use biochar as a carrier. Achieve synergistic and directed humification of organic matter while reducing pollutant gas emissions during the composting process.

2) Based on the concept of “waste-to-resource utilization”, identify the best additive materials to regulate humification and reduce pollutants during various stages of composting, and then construct and optimize the phased material-mediated technology system to realize the targeted regulation of the composting process.

3) Explore the microbial mechanisms of pollutant gas emission mediated by exogenous materials, such as physical, chemical, and biological materials. Elucidate the rules of pollutant emission and innovate technologies for pollutant gas target regulation and nutrient sequestration.

4) Research and develop ventilation systems, monitoring systems, and remote-control equipment and systems. Innovative intelligent membrane materials including nanoporous carbon scaffold films.

Using relevant technological breakthroughs is key to the safe and resourceful utilization of agricultural organic waste. It can also provide technical support and solutions for the ecological development of agricultural resources.

(6) Creation of novel and efficient animal vaccines

Animal vaccine a kind of biological products used to protect animals from specific diseases or pathogen infections. They work by introducing inactivated or attenuated pathogens, partial components, or genetic information, which activate the animal’s immune system to generate immune protective responses, thereby enhancing the animal’s resistance to diseases. In China, the livestock and poultry farming industry continues to grow in scale and density, meanwhile, the population of companion animals is continually increasing. Major impacted animal diseases and zoonotic diseases seriously threaten the stable development of the industry and human health. Efficient and safe vaccine immunization is one of the core measures for disease prevention and control. Compared to Europe and America, China’s innovation level is relatively insufficient in the fields of novel animal vaccine original technology platforms, antigen selection and delivery, and adjuvant development. There is significant room for improvement. Current technological directions and development trends in this field mainly include: ① research and development of universal technologies and platform for screening and delivery of novel vaccines; ② precise target selection and design of novel vaccines for animals; ③ development of novel vaccines with safety and effectiveness, including mucosal immune vaccines, subunit vaccines, gene-deleted marker vaccines, multi-epitope vaccines, live carrier vaccines, nucleic acid vaccines, transgenic plant-edible vaccines, and others; ④ strategies for DVAL vaccines that can distinguish vaccinated and infected animal along with the differential diagnostic test kits; ⑤ establishment of a comprehensive system for monitoring animal diseases and evaluating vaccine immunization effectiveness; and ⑥ development of key technologies for vaccine production processes. Technological progress in these field will provide technical support and solutions for the prevention, control and eradication of major animal diseases in our country.

(7) Preparation of feed by pre-digestion fermentation bioprocessing

Feed pre-digestion technology is the inevitable result of the increasing market demand of low and non-resistant feeding and personalized characteristic livestock products. Biological pre-digestion fermentation of feed is the pre-digestion of feed through enzymatic hydrolysis or microbial fermentation technology, which degrades macromolecular nutrients into small molecular substances easily absorbed by animals, reduces toxic and harmful substances and anti-nutritional factors in feed, improves feed palatability, increases crude protein content in feed, improves digestion and absorption efficiency of feed nutrients, and promotes efficient growth of livestock and poultry. The bioprocessing and preparation system of feed pre-digested fermentation mainly includes: ① analyzing the characteristics of pre-digested feed raw materials, judging the potential digestion key points according to the spatial structure and chemical bond types of raw materials, and identifying the key enzymes required; ② screening of high-quality and safe fermentation strains, in-depth study of their enzyme production types and characteristics, mining enzyme production genes and regulation of efficient expression, including bacteria-enzyme coordination; ③ optimize the fermentation process, regulate the fermentation conditions such as temperature, pH and time, create a good fermentation environment, and give full play to the high catalytic efficiency and potential of the enzyme; and ④ evaluation of application effects, multi-level evaluation of the effectiveness and safety of pre-digested fermentation products through in vivo and in vitro, multi-level livestock and poultry breeding and validation tests. The development of safe, healthy, efficient and environmentally friendly new feed products is of great significance to promote the efficient and sustainable development of livestock and poultry industry and improve the economic benefits of animal husbandry.

(8) Genomic mating breeding technology for livestock and poultry

Genomic mating (GM) breeding technology for livestock and poultry refers to the optimized selection and mating of candidate individuals using their genomic information. It enables control of the rate of inbreeding in the population and facilitates long-term and sustainable genetic progress. However, with the development of genomic selection technology, while pursuing extreme genetic progress for specific traits, there is a significant decrease in the genetic diversity of the population, limiting the selection space for other traits and posing risks of inbreeding depression among high-yielding animals due to higher kinship coefficients. As a result, the optimization of mating based on genomic information has gained increasing attention. It involves comprehensive considerations such as controlling inbreeding, maintaining population genetic diversity, and maximizing genetic progress to formulate sustainable breeding plans. Currently, the U.S. Dairy Cattle Breeding Council has implemented the application of genomic mating in dairy cattle populations, and compared to random mating, genomic mating technology has been shown to increase the value of dam-offspring pairs by $78 per head. Achieving optimized selection and mating in breeding animals through GM requires consideration of not only the genetic characteristics of the animals themselves but also the genetic relationships and complementarity between mating partners, as well as specific features and traits unique to the breeds. This minimizes the reduction in population genetic heterozygosity, the increase in inbreeding coefficients, and the changes in genetic background gene frequency between selection generations. Therefore, GM is a highly complex problem. Current research mostly focuses on the additive genetic effects of single traits, while future research directions will include multi-trait systems and non-additive genetic effects. In addition to optimizing mating schemes, GM methods can also be applied in the following areas: ① discovering unknown ancestors or correcting inaccurate pedigrees; ② estimating the breed composition of hybrid animals or confirming breed purity; ③ avoiding inbreeding and estimating non-additive genetic effects at the genomic level; ④ identifying and monitoring individuals with new defects or economically important traits; and ⑤ predicting the probability of occurrence of high-yielding or low-yielding individuals, among other scenarios or application domains. Therefore, GM is applicable not only for constructing core breeding systems in endangered or critically endangered local species but also for building core breeding systems for high-yielding animals. This will lay the technological foundation for promoting and applying GM in optimized breeding practices.

(9) Key technologies for unmanned farms

Currently, in China, the rural labor force is experiencing a growing trend of “aging, feminization, and sidelineization”, while the issue of “who will cultivate the land” has become a common challenge for both our country’s agriculture and global agriculture. Practical experience has shown that adopting technologies such as intelligent agricultural machinery and smart decision-making management in unmanned farming can significantly enhance labor productivity, land yield, and resource utilization efficiency. The effective approach to addressing the issue of “who will cultivate the land” is the development of smart agriculture, with unmanned farms being a crucial avenue for achieving this. Key technologies for unmanned farms include:

1) Digital sensing technology, including accurate sensing technology of the operating environment, operating objects and operating machinery information of unmanned farms, as well as internet of things (IoT) technology to realize the digitization of the whole link and the whole process.

2) Intelligent decision-making technology, which combines technologies such as big data, cloud computing, and artificial intelligence. This involves research in data mining, knowledge discovery, and other techniques to achieve intelligent agricultural production decision-making.

3) Precision operations technology, utilizing intelligent agricultural machinery equipment, multi-machine coordination, autonomous driving, and precise operation technologies. This enables unmanned intelligent equipment to perform autonomous and precise operations.

4) Smart management technology, including crop growth management, agricultural machinery management, and farm management. This facilitates highly coordinated operations for agricultural production processes like plowing, sowing, managing, and harvesting, making the entire farm production process smart and efficient.

Breakthroughs in core technologies of unmanned farms will provide technical support and solutions for addressing the "who will cultivate the land" issue, accelerating the large-scale application of unmanned farms and promoting the development of smart agriculture.

(10) Bio-refinery of wood waste

Bio-refinery of wood waste, also known as forest biomass refining (compared with petroleum refining), is a technology that uses waste wood fiber biomass generated during wood harvesting and processing as raw materials through thermochemical and biological treatment methods to produce liquid fuels (such as fuel ethanol, biodiesel, etc.), platform chemicals (such as furfural, furfuryl alcohol, etc.), feed additives, bio-based materials, and other products. This technology includes two routes: bioconversion and thermochemical conversion. Bioconversion is a technology that uses microorganisms or enzymes as catalysts to convert biomass into green products through industrial biotechnology. The main research directions of bioconversion include: the technology of extracting, separating, and utilizing secondary metabolites from forest sources mainly included of active components such as flavonoids, tannins, terpenoids, and phenylpropanoids; development and preparation technology of material precursor monomers included of lactic acid, ethylene glycol, succinic acid, and furan dicarboxylic acid materials; fuel preparation technology mainly focused on the preparation of fuel chemicals such as natural gas, cellulose ethanol, and butanol. Thermochemical conversion is a technology that converts wood fibers through pyrolysis, liquefaction, gasification, and other methods. The main research directions of thermochemical conversion include: pyrolysis-gas-carbon coproduction technology for preparing high-quality gas and advanced carbon material precursors; liquefaction technology for preparing platform chemicals such as furfural and phenols, as well as liquid fuels; the preparation technology of bio-based functional materials using platform chemicals as monomers or cellulose, lignin, etc. as matrices. In recent years, with the innovation of biomass refining technology, China has shortcomings in basic theoretical innovation, key core and forward-looking technology reserves. The main directions for future industry development are: ① with the main goal of diversified utilization of raw materials, efficient transformation systems, and high value products, building a full industry chain technology system from renewable raw materials to end products; ② research and development of cross coupling technologies for bioconversion and thermochemical conversion, as well as key equipment development and technical system construction.

(11) Ecological breeding technology of aquatic animals

Ecological breeding technology of aquatic animals is to reduce manual operations and simulate natural environmental conditions of ovulation to maintain the animal welfare of the parents, reduce the loss of the parents, make the parents reusable, and achieve a breeding technology that "simulate nature with less artificial spawning". The concept is to strive to allow aquatic animals to be fertilized naturally in a simulated ecological environment, with little or no use of hormones to induce ovulation, and to collect sperm and eggs with as little human intervention as possible, so that aquatic animal breeding can return to nature. In recent years, with the rapid development of the breeding industry, the demand for aquatic animal seeds in my country has increased sharply. However, traditional breeding operations are not conducive to the sustainable utilization of parents, causing huge economic losses and are not conducive to animal welfare; in addition, artificial hormones The use not only affects the normal physiological activities of aquatic animals, but also brings the risk of environmental pollution. Therefore, carrying out ecological breeding of aquatic animals is an important strategy for the industry to transform into a green and ecological industry. The core technologies include: ① ecological parent breeding technology; ② simulated natural ecological conditions to induce ovulation and fertilization;

and ③ ecological hatching and fry culturing. Relevant technological breakthroughs will promote the ecological transformation of aquatic animal breeding and promote the high-quality development of ecological fisheries.

2.2 Interpretations for three key engineering development fronts

2.2.1 Molecular design of green pesticides based on structural biology

The process of molecular design of green pesticides based on structural biology primarily involves the rational and precise development of environmentally friendly pesticides by utilizing three-dimensional structural information of pesticide molecular targets. The creation of green pesticides constitutes a highly intricate multidisciplinary integrated system engineering endeavor characterized by substantial investment, lengthy duration, and significant risk. According to statistics, the development of a new pesticide using traditional methods requires the synthesis of 140 000 compounds and lasts over 10 years with an investment of nearly 300 million USD. In recent years, research and development costs and cycles have continued to increase. However, by employing structural biology methods to acquire key site information for the target, combined with high-throughput virtual screening and computer-aided drug design, the research and development cycle can be expedited, and costs can be reduced.

The development stage of protein structural biology and computer-aided drug design research both commenced in the 1960s. Initially, the integration of these two technologies to establish drug design based on structural biology was primarily employed in pharmaceutical development, subsequently finding applications in the field of pesticides. The article “Current challenges and trends in the discovery of agrochemicals” states that structure-based design is a growing discipline within crop protection research (Lamberth et al., Science, 2013). Currently, structure-based molecular design has become the dominant approach for developing novel green pesticides, leading to the successful creation of numerous innovative green pesticides. For example, based on the structure of succinate dehydrogenase (SDH), fluorophenylamide and chlorophenylamide, which is efficient for the control of rice sheath blight and potato late blight were designed and developed using the method of pharmacophore-linked fragment virtual screening (PFVS). Additionally, new skeleton structures of herbicides, quinoxalone and methylquinoxalone, were developed using a molecular design strategy targeting the conformational changes of the key residue Gln293 in the active pocket of 4-hydroxyphenylpyruvate dioxygenase (HPPD). Moreover, by employing virtual screening based on the structure of the abscisic acid (ABA) receptor, a new ABA receptor agonist called Opabactin (OP) was identified.

By leveraging the structure of a molecular target, dozens or even hundreds of pesticides can be designed and developed. In the case of insecticides, more than 80% of the world’s insecticides utilize four structure available molecular targets, namely nicotinic acetylcholine receptor, acetylcholinesterase, GABA-gated chloride ion channel, and pressure-controlled sodium ion channel. Cryo-electron microscopy technology and artificial intelligence have significantly advanced this field in recent years. Cryo-electron microscopy enables the analysis of previously challenging molecular targets in pesticide research, such as chitinase synthase (the potential target for benzoylurea pesticides) and ryanodine receptor (the target for bisamide pesticides). The application of artificial intelligence technology extends beyond target structure prediction, injecting new vitality into the iteration and innovation of pesticide molecular design methods, thereby further expediting the development cycle.

The core patents related to “molecular design of green pesticides based on structural biology” are mainly produced by countries and institutions shown in Tables 2.2.1 and 2.2.2, respectively. Cooperation networks among major countries and institutions are shown in Figures 2.2.1 and 2.2.2. The USA has the most disclosed core patents, with 54 patents, accounting for 48.65%. Denmark ranks second with 24 patents, accounting for 21.62%. Germany ranks third with 16 patents, accounting for 14.41%. China holds 7 patents, ranking fifth globally and accounting for 6.31%. There is cooperation between the USA, Denmark, Sweden, Germany, and Australia; there is no cooperation among other countries. The institution that produced the most core patent was the Novozymes BioAg Limited from Denmark, with a total of 29 patents, followed by University of California and Bayer Crop Science. The top four institutions in terms of citation ratio are Novozymes BioAg Limited (50.44%), University of California (13.64%), Concentric Ag Corporation (7.58%), and Inocucor Technologies Incorporated (7.58%). The institution with the highest citations per patent

Table 2.2.1 Countries with greatest output of core patents on "molecular design of green pesticides based on structural biology"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	54	48.65	1 064	48.87	19.70
2	Denmark	24	21.62	944	43.36	39.33
3	Germany	16	14.41	146	6.71	9.12
4	UK	8	7.21	41	1.88	5.12
5	China	7	6.31	21	0.96	3.00
6	Australia	3	2.70	47	2.16	15.67
7	Belgium	2	1.80	42	1.93	21.00
8	New Zealand	2	1.80	0	0.00	0.00
9	Canada	1	0.90	33	1.52	33.00
10	Sweden	1	0.90	10	0.46	10.00

Table 2.2.2 Institutions with greatest output of core patents on "molecular design of green pesticides based on structural biology"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Novozymes BioAg Limited	29	26.13	1 098	50.44	37.86
2	University of California	10	9.01	297	13.64	29.70
3	Bayer Crop Science	10	9.01	87	4.00	8.70
4	Badische Anilin-und-Soda-Fabrik (BASF)	9	8.11	113	5.19	12.56
5	E.I. Dupont De Nemours and Company	9	8.11	79	3.63	8.78
6	The Secretary of State for Environment Food and Rural Affairs	8	7.21	41	1.8	5.12
7	University of Durham	8	7.21	41	1.88	5.12
8	AgroSpheres Incorporated	7	6.31	84	3.86	12.00
9	Concentric Ag Corporation	5	4.50	165	7.58	33.00
10	Inocucor Technologies Incorporated	5	4.50	165	7.58	33.00

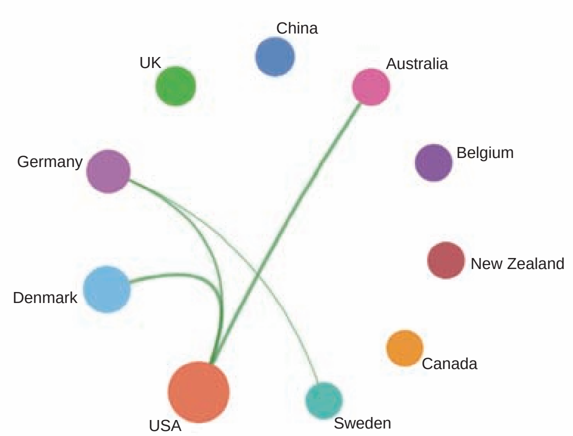

Figure 2.2.1 Cooperation network among major countries in the engineering development front of "molecular design of green pesticides based on structural biology"

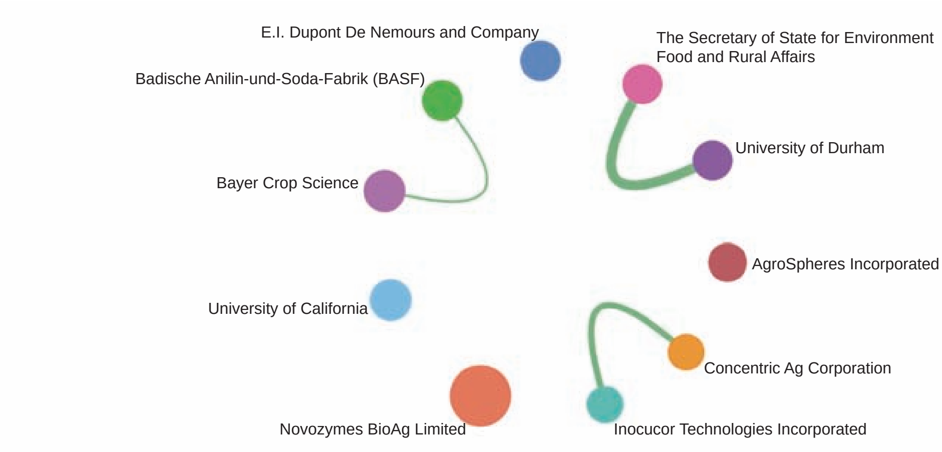

Figure 2.2.2 Cooperation network among major institutions in the engineering development front of "molecular design of green pesticides based on structural biology"

is Novozymes BioAg Limited with 37.86 times. There is cooperation between Bayer Crop Science and Badische Anilin-und-Soda-Fabrik (BASF), the Secretary of State for Environment Food and Rural Affairs and University of Durham, Concentric Ag Corporation, and Inocucor Technologies Incorporated.

Figure 2.2.3 shows the development path of the front of "molecular design of green pesticides based on structural biology". In the next ten years, the engineering frontier of structure-based molecular design of green pesticides is expected to make progress in the following two aspects:

1) Technological innovation: With the continuous development of emerging technologies such as artificial intelligence, computer-aided technology, and big data, the field of structure-based green pesticide molecular design is also constantly innovating. For example, artificial intelligence and computer-aided technology can be used to develop new pesticide molecular design methods and new platforms for rational drug design; based on computer-aided design platforms, a small molecule compound library covering a wide chemical space can be constructed and high-throughput screening methods can be developed to design new pesticide molecular skeletons that are easy to modify and derive.

2) Environmental protection: Green pesticide molecular design also needs to consider its impact on the environment. For example, new methods for rational drug design based on target resistance prediction can be developed to reduce the risk of resistance and interactive resistance in new pesticide creation from the source. In addition, the environmental safety of pesticide molecules can be evaluated by studying the metabolic behavior of pesticides in the environment, the safety of metabolic products, and factors such as metabolic half-life.

In summary, the field of structure-based green pesticide molecular design is constantly innovating and developing, aiming to achieve safer, more efficient, and more environmentally friendly pesticide production through technological innovation and

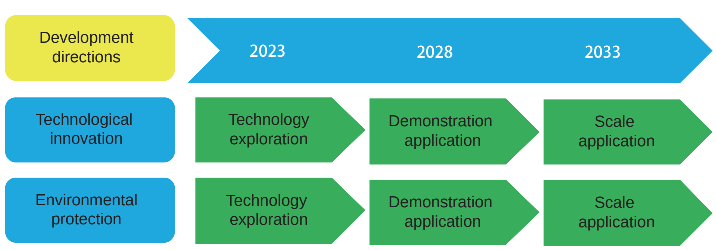

Figure 2.2.3 Roadmap of the engineering development front of "molecular design of green pesticides based on structural biology"

environmental protection. This field still faces many challenges and requires continuous exploration and innovation to make greater progress.

2.2.2 Preparation of feed by pre-digestion fermentation bioprocessing

Feed pre-digestion technology is the inevitable result of the increasing market demand of low and non-resistant feeding and personalized characteristic livestock products. Biological pre-digestion fermentation of feed is the pre-digestion of feed through enzymatic hydrolysis or microbial fermentation technology, which degrades macromolecular nutrients into small molecular substances easily absorbed by animals, reduces toxic and harmful substances and anti-nutritional factors in feed, improves feed palatability, increases crude protein content in feed, improves digestion and absorption efficiency of feed nutrients, and promotes efficient growth of livestock and poultry. Pre-digested feed contains both protein raw materials (fermented soybean meal, fermented cottonseed protein, baked soybean, hydrolyzed fish protein meal, cottonseed enzymatic hydrolysis protein, wheat hydrolyzed protein) and energy raw materials (baked corn, pre-gelatinized rice), which are important components of feed products. Calculated according to 20% of the output value of feed products, the potential of the output value of pre-digested raw materials is as high as 200 billion yuan.

The development of feed pre-digestion fermentation technology in China can be summarized into three stages. The first stage was saccharification feed and silage in the 1980s. In the second stage, in the 1990s, probiotics were made into bacteriotics and added into the base diet as feed additives until the development of the current stage of microbial fermentation pre-digested feed. In recent years, due to the greatly increased social demand for livestock products, the lack of high-quality protein feed raw materials and the harm caused by long-term use of antibiotics have become increasingly prominent, and feed pre-digestion fermentation technology has been rapidly developed. At present, feed pre-digested fermentation has been widely studied and applied in livestock production. Researchers can improve intestinal health and growth performance of pigs by adding lactic acid bacteria to fermented liquid feed and grape skin fermented feed. In laying hens, adding soybean meal protein fermented feed to basic diet can increase laying rate, reduce feed to egg ratio and ammonia concentration in feces.

The bioprocessing and preparation system of feed pre-digested fermentation mainly includes: ① analyzing the characteristics of pre-digested feed raw materials, judging the potential digestion key points according to the spatial structure and chemical bond types of raw materials, and identifying the key enzymes required; ② screening of high-quality and safe fermentation strains, in-depth study of their enzyme production types and characteristics, mining enzyme production genes and regulation of efficient expression, including bacteria-enzyme coordination; ③ optimize the fermentation process, regulate the fermentation conditions such as temperature, pH and time, create a good fermentation environment, and give full play to the high catalytic efficiency and potential of the enzyme; and ④ evaluation of application effects, multi-level evaluation of the effectiveness and safety of pre-digested fermentation products through in vivo and in vitro, multi-level livestock and poultry breeding and validation tests. The development of safe, healthy, efficient and environmentally friendly new feed products is of great significance to promote the efficient and sustainable development of livestock and poultry industry and improve the economic benefits of animal husbandry.

The major countries and institutions of the core patents related to "preparation of feed by pre-digestion fermentation bioprocessing" are shown in Tables 2.2.3 and 2.2.4, respectively. The top three countries in terms of core patent disclosure are China (64 patents, accounting for 87.67%), the USA (6 patents, accounting for 8.22%), and Republic of Korea (2 patents, accounting for 2.74%). There is no cooperation between countries in this direction. The institutions with the largest number of core patents is Locus IP Company (4 patents). Qingdao Agricultural University's core patent output ranked second (2 patents); and the other institutions have 1 core patent. The top four institutions in terms of citations were Locus IP Company (10.53%), E.I. Dupont De Nemours and Company (6.58%), Freshwater Fisheries Research Center of Chinese Academy of Fishery Sciences (6.58%), and Nanjing Institute of Fishery Sciences (6.58%). The institutions with the highest citations per patent were E.I. Dupont De Nemours and Company, Freshwater Fisheries Research Center of Chinese Academy of Fishery Sciences, and Nanjing Research Institute of Fishery, all with 5 citations. Nanjing Research Institute of Fishery and Freshwater Fisheries Research Center of Chinese Academy of Fishery Sciences have cooperative relations, but there is no cooperative relationship between other institutions (Figure 2.2.4).

Table 2.2.3 Countries with greatest output of core patents on “preparation of feed by pre-digestion fermentation bioprocessing”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	64	87.67	62	81.58	0.97
2	USA	6	8.22	13	17.11	2.17
3	Republic of Korea	2	2.74	0	0.00	0.00
4	Slovakia	1	1.37	1	1.32	1.00

Table 2.2.4 Institutions with greatest output of core patents on “preparation of feed by pre-digestion fermentation bioprocessing”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Locus IP Company	4	5.48	8	10.53	2.00
2	Qingdao Agricultural University	2	2.74	1	1.32	0.50
3	E.I. Dupont De Nemours and Company	1	1.37	5	6.58	5.00
4	Freshwater Fisheries Research Center, CAFS	1	1.37	5	6.58	5.00
5	Nanjing Research Institute of Fishery	1	1.37	5	6.58	5.00
6	Hangzhou Genglan Biotechnology Company Limited	1	1.37	3	3.95	3.00
7	Institute of Dryland Farming Hebei Academy of Agricultural and Forestry Sciences	1	1.37	3	3.95	3.00
8	Kaifeng Jar Jun Biotechnology Company Limited	1	1.37	3	3.95	3.00
9	Shenzhen Hemin Biotechnology Company Limited	1	1.37	3	3.95	3.00
10	Hubei Xipu Biological Technology Co., Ltd.	1	1.37	2	2.63	2.00

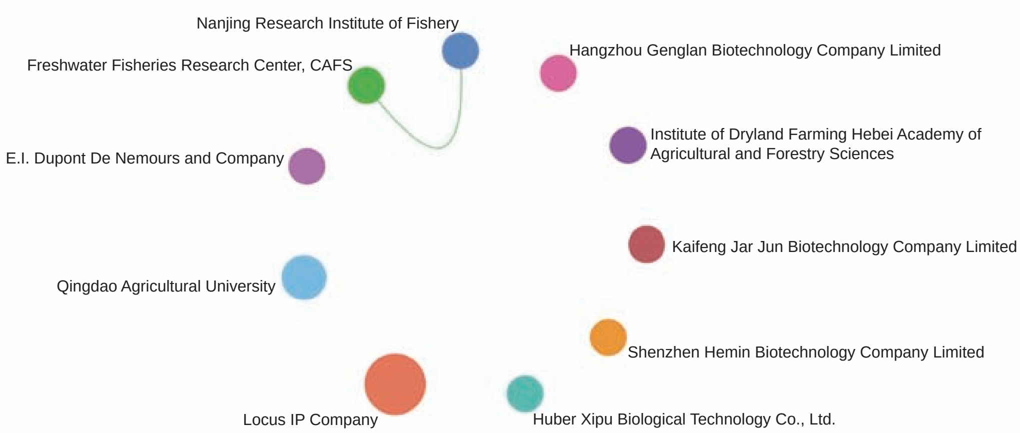

Figure 2.2.4 Cooperation network among major institutions in the engineering development front of “preparation of feed by pre-digestion fermentation bioprocessing”

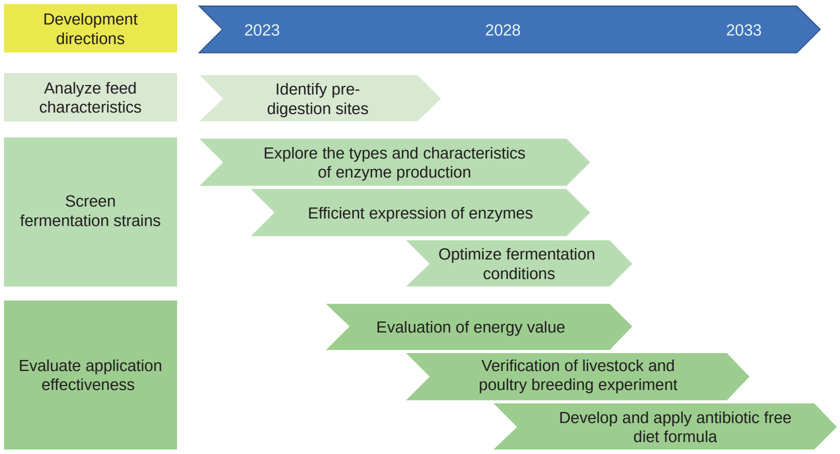

Figure 2.2.5 Roadmap of the engineering development front of “preparation of feed by pre-digestion fermentation bioprocessing”

Figure 2.2.5 shows the roadmap of the engineering development front of “preparation of feed by pre-digestion fermentation bioprocessing”.

2.2.3 Ecological breeding technology of aquatic animals

Aquatic animals provide important high-quality protein and high-quality fat for the people. Breeding work on fish, shellfish, shrimps and crabs carried out in recent years has not only greatly increased production, but also improved the quality of cultured products. As the people’s demand for a beautiful ecological environment grows, there is an urgent need for aquatic animal breeding to transform from traditional methods to ecological methods. For example, grass carp, which has the largest aquaculture output in my country, requires hormone induction and artificial insemination during the reproduction process. During this process, it is possible to damage the internal organs of the broodstock, and it is also easy to cause skin infection, resulting in the death of a large number of broodstock after birth, which is not conducive to the sustainable utilization of the broodstock, brings huge economic losses, and is not advantageous to animal welfare. In addition, the use of artificial hormones not only affects the normal physiological activities of fish, but also brings the risk of environmental pollution. The purpose of ecological breeding of aquatic animals (Ecological Breeding Technology of Aquatic Animals) is to simulate the natural spawning by reducing artificial operations, maintain the animal welfare of the parents, reduce the loss of the parents, and make the parents reusable, so as to “simulate nature with less artificial spawning”. Compared with traditional breeding techniques, ecological breeding started later. Various ecological breeding programs currently being tried have made some progress and can effectively protect high-quality parent resources. The goal of ecological breeding is to strive to allow aquatic animals to be fertilized naturally in a simulated ecological environment by simulating natural ecological breeding conditions, using less or no hormones to induce ovulation, and using less human intervention to collect sperm and eggs, so that aquatic animal breeding can return to nature.

The advantages of ecological breeding of aquatic animals are mainly reflected in following aspects:

1) Low damage to parents. Compared with traditional artificial breeding, ecological breeding of aquatic animals only requires building the native environment of the parents, using less or no artificial hormones, and trying to avoid artificial intervention in insemination, which can minimize the loss of parents.

2) Environmentally friendly. Ecological animal breeding technology strictly controls the dosage of hormones during the breeding process to avoid burdening the environment.

3) The cost is lower. It improves the survival rate of parents after induced ovulation and preserves large-scale parent resources for subsequent breeding. The animal ecological breeding technology only requires a small amount of manual operations, reducing costs.

4) Animal welfare. Traditional breeding technology involves a lot of manual operations, while ecological breeding technology is beneficial to ensuring fish welfare through ecological development.

In summary, ecological breeding of aquatic animals is particularly suitable for breeding species with precious parent resources. At the same time, it is also an important technical means that meets the needs of promoting green development and building ecological civilization. It is an aquatic animal breeding strategy with great potential.

Ecological breeding of aquatic animals is a new technology and research hotspot that has emerged with the rise of ecological and environmental protection concepts. It has been carried out in some aquatic animals and has made important progress. However, due to the short development time, it is still in its infancy. Since 2020, nearly 52 results have been published in the field of ecological breeding of aquatic animals. Most of these studies focus on some species that can ovulate and fertilize autonomously under artificial breeding conditions. However, there are few reports on species that require artificial induction, especially fish. The reasons for the lag include: most breeding researchers and operators in breeding farms have adapted to high-intensity, high-yield seed production operations. In order to pursue short-term interests ignore ecological benefits; the understanding of the concept of ecological breeding of aquatic animals is relatively weak, and corresponding systematic research cannot be carried out; there are many aquaculture species, and it is necessary to carry out relevant research on each species and establish an ecological breeding technology system Long-term research, therefore ecological breeding research started late.

In order to overcome difficulties and promote the development of ecological breeding technology for aquatic animals, there is an urgent need to:

1) Carry out research on ecological breeding technology, break through technical bottlenecks, clarify key factors and parameters of ecological breeding conditions for key breeding species, and ultimately form a low-cost, standardized, and easy-to-use technology as well as ecological breeding technology process for operation.

2) Build an ecological breeding technology system. On the basis of establishing the ecological breeding technology process, we should further carry out small and pilot tests, conduct large-scale experiments according to different species, regions, and breeding models, and obtain systematic ecological breeding model.

3) We need to carry out demonstration and promotion of ecological breeding technology in major breeding bases and nurseries, establish high-quality ecological breeding nurseries, and provide standardized examples for the implementation of ecological breeding technology for aquatic animals. In addition, since breeding work involves the consumption of parents, offspring, labor, etc., it requires a large amount of capital investment. Long-term and stable cooperation and investment between research institutions and breeding companies should be promoted.

Table 2.2.5 Countries with greatest output of core patents on “ecological breeding technology of aquatic animals”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	52	100	25	100	0.48

Table 2.2.6 Institutions with greatest output of core patents on "ecological breeding technology of aquatic animals"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Fisheries Research Institute, Anhui Academy of Agricultural Sciences	2	3.85	0	0.00	0.00
2	Shenzhen Xingrisheng Industrial Company Limited	2	3.85	0	0.00	0.00
3	Chongqing University of Arts and Sciences	1	1.92	4	16.00	4.00
4	Jiangsu Yuehai Feeds Company Limited	1	1.92	4	16.00	4.00
5	Zhejiang Mariculture Research Institute	1	1.92	4	16.00	4.00
6	South China Agricultural University	1	1.92	3	12.00	3.00
7	Southwest University	1	1.92	2	8.00	2.00
8	Tianjin Aquatic Product Research Institute	1	1.92	2	8.00	2.00
9	Mianyang Anzhou District Xinmin Agricultural Technology Company Limited	1	1.92	1	4.00	1.00
10	Qingdao Ruizi Treasure Development Company Limited	1	1.92	1	4.00	1.00

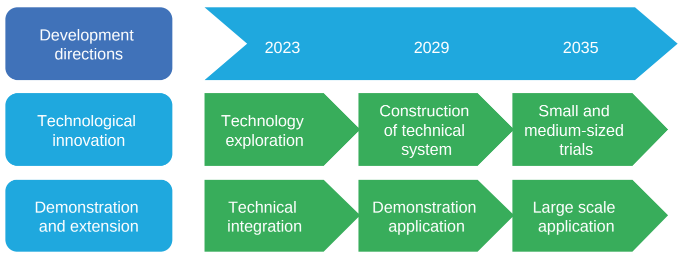

Figure 2.2.6 Roadmap of the engineering development front of "ecological breeding technology of aquatic animals"

The main countries and institutions of the core patents related to "ecological breeding technology for aquatic animals" are shown in Tables 2.2.5 and 2.2.6, respectively. There is no cooperation among major institutions. Figure 2.2.6 shows the development path of the front of the "ecological breeding technology for aquatic animals".

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VIII. Medicine and Health

1 Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

The Top 10 engineering research fronts in the field of medicine and health include basic medicine, clinical medicine, biomedical engineering, bioinformatics, immunology, and developmental biology (Table 1.1.1). These 10 fronts involve "multi-omics traits of complex diseases", "mechanism of persistent virus infection and reactivation and analysis of intervention targets", "the core human microbiome and host–microbiome interaction", "reprogramming of aging", "regulation and remodeling of immune homeostasis in organ transplantation", "monoclonal antibody therapy for Alzheimer's disease", "biomacromolecular phase separation and membraneless organelles", "research on the mechanism of organoid construction and development in primates", "the human pangenome and disease pangenome", and "mechanisms of chromatin dynamic modification on tissue and organ development". All core papers on these fronts published between 2017 and 2022 are listed in Table 1.1.2.

(1) Multi-omics traits of complex diseases

Complex diseases, characterized by the interplay of genetic and environmental factors, pose significant challenges to healthcare due to the absence of precise treatment modalities. These conditions adversely impact patients' quality of life and exert substantial social and economic burdens. The advent of high-throughput sequencing technologies has elevated multi-omics to a pivotal role in the study of complex diseases, enabling nuanced trait dissection and facilitating clinical applications. Specifically, multi-omics approaches contribute to the identification of predictive biomarkers and the screening of therapeutic targets, thereby becoming a focal point in contemporary medical research that has garnered significant investment and international collaboration, including active participation from China.

Table 1.1.1 Top 10 engineering research fronts in medicine and health

No.	Engineering research front	Core papers	Citations	Citations per year	Mean year
1	Multi-omics traits of complex diseases	9 428	848 396	89.99	2018.5
2	Mechanism of persistent virus infection and reactivation and analysis of intervention targets	504	40 148	79.66	2018.2
3	The core human microbiome and host–microbiome interaction	82	6 879	83.89	2018.6
4	Reprogramming of aging	106	7 255	68.44	2019.1
5	Regulation and remodeling of immune homeostasis in organ transplantation	174	13 417	77.11	2018.8
6	Monoclonal antibody therapy for Alzheimer's disease	170	9 066	53.33	2019.0
7	Biomacromolecular phase separation and membraneless organelles	614	74 515	121.36	2018.7
8	Research on the mechanism of organoid construction and development in primates	40	1 784	44.60	2020.3
9	The human pangenome and disease pangenome	165	17 103	103.65	2018.6
10	Mechanisms of chromatin dynamic modification on tissue and organ development	290	32 576	112.33	2018.2

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in medicine and health

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Multi-omics traits of complex diseases	2 626	2 421	2 178	1 439	631	133
2	Mechanism of persistent virus infection and reactivation and analysis of intervention targets	193	138	96	49	24	4
3	The core human microbiome and host–microbiome interaction	20	20	21	15	6	0
4	Reprogramming of aging	22	24	19	16	17	8
5	Regulation and remodeling of immune homeostasis in organ transplantation	37	45	37	25	26	4
6	Monoclonal antibody therapy for Alzheimer's disease	35	40	29	29	23	14
7	Biomacromolecular phase separation and membraneless organelles	118	174	162	115	40	5
8	Research on the mechanism of organoid construction and development in primates	2	3	6	5	17	7
9	The human pangenome and disease pangenome	43	43	37	29	11	2
10	Mechanisms of chromatin dynamic modification on tissue and organ development	99	82	69	31	9	0

Looking to the future, it is imperative for research institutions to establish standardized, large-sample, multi-center cohorts and biobanks that are spatiotemporally paired. Comprehensive assessments should be conducted using omics technologies and phenotypic data to elucidate the traits of complex diseases. Advanced computational methods, such as network analysis and machine learning, should be employed to delineate intricate disease networks and identify potential pathways for intervention. Furthermore, the development of both *in vitro* and *in vivo* experimental models is crucial for exploring innovative strategies for precision diagnosis and treatment.

(2) Mechanism of persistent virus infection and reactivation and analysis of intervention targets

Persistent viral infection occur repeatedly and are difficult to cure, and can even trigger tumors, posing a serious threat to human health. The mechanisms that lead to persistent viral infection and reactivation are extremely complicated, involving factors such as viral gene replication regulation and its interaction with the host immune system. By elucidating the relevant mechanisms, new targets and strategies can be created for the prevention and control of related infectious diseases, not only provide more effective treatments for known viral diseases, but also provide strategic reserves for dealing with future emerging viruses.

The mechanism of persistent viral infection involves the long-term persistence of the viral genome, the evasion of cellular and host defense mechanisms, and the inhibition of the virus's cytopathic effect. Persistent viral infection can result in the virus being reactivated, which can be lead to pathological effects and complicate the disease process.

The main interventions for latent infection currently include targeting viral replication and targeting the virus-specific immune response. The analysis of intervention targets and the mechanism of persistent virus infection and reactivation are crucial frontiers in virology research, and countries with advanced science and technology have made remarkable achievements. China has the ability to catch up with similar international research in this field. It is necessary to develop new technologies, such as gene editing, multi-omics, organoid culture, and novel humanized animal models, from a systems biology perspective to reveal the mechanisms of viral latency and persistent infection, viral reactivation, inflammation-cancer transformation, virus-host interactions, and pathogenesis at the molecular, cellular, organ, animal, and human levels. Discovering effective intervention targets and new diagnostic and therapeutic markers, as well as developing novel antiviral strategies, is crucial simultaneously.

(3) The core human microbiome and host–microbiome interaction

The human microbiome serves as a cornerstone in the maintenance of host health, and advances in high-throughput omics sequencing have catalyzed a plethora of studies aimed at elucidating the composition and functions of human gut microbiota. These studies also seek to decode host-microbiota interactions and formulate microbiome-centric intervention strategies. However, the concept of a core microbiome, comprising microbiota shared among diverse individuals and exerting broad health impacts, remains inadequately defined. Consequently, the identification of this core microbiota and the development of microbiome-targeted therapies have emerged as critical frontiers in medical research, attracting significant international funding.

China, characterized by its large population and diverse dietary, cultural, and lifestyle factors, necessitates the establishment of a high-caliber human microbiome research platform tailored to its demographic. Employing cutting-edge technologies such as whole-genome sequencing, high-throughput culturomics, and artificial intelligence algorithms is essential for advancing our comprehension of microbiota-host interactions. Additionally, the promotion of engineered live biotherapeutic products and the incorporation of precision medicine strategies for disease prevention through microbiome modulation are imperative. Collectively, these endeavors are pivotal for broadening the clinical applicability of microbiota-based interventions and propelling the advancement of microbiome-centered medicine.

(4) Reprogramming of aging

The global rise in aging populations and the concomitant prevalence of age-related diseases present formidable challenges to healthcare systems worldwide. Aging is a multifaceted process characterized by programmatic functional decline, heterogeneity, complexity, and susceptibility to disease. Recent advancements in aging reprogramming technologies have shown promise in decelerating or even reversing age-associated declines at cellular, tissue, and organismal levels, thereby laying the groundwork for targeted interventions in aging and age-related pathologies.

Current research in aging reprogramming encompasses several key domains: ① integration of interdisciplinary technologies spanning biology, medicine, and computer informatics to elucidate aging regulatory mechanisms and identify biomarkers at multiple biological scales; ② application of gene-editing technologies and targeted delivery methods to modulate the expression of aging-related and rejuvenation-associated genes; ③ introduction of reprogramming factors to alter chromatin states and epigenetic markers linked to cellular senescence; ④ utilization of senolytic drugs, inhibitors of the senescence-associated secretory phenotype (SASP), and senolytic vaccines to eliminate senescent cells and facilitate tissue regeneration; and ⑤ enhancement of gut microbiota homeostasis and the modulation of nutrition-sensing pathways to reshape the tissue microenvironment.

Chinese researchers have made significant strides in understanding the mechanisms of aging and developing intervention strategies, notably in the identification of aging biomarkers, the regulation of aging-associated genes, the screening of geroprotective drugs, and the advancement of epigenetic reprogramming techniques. However, the majority of these studies have been conducted in animal models, with a paucity of translational research and clinical validation. As such, rigorously designed clinical trials are imperative to assess the efficacy and safety of aging reprogramming strategies, thereby accelerating both basic and translational research in human aging interventions and addressing the challenges posed by demographic aging.

(5) Regulation and remodeling of immune homeostasis in organ transplantation

Organ transplantation represents a pivotal therapeutic approach for individuals facing end-stage organ failure. Nevertheless, the persistent challenges of organ rejection and the adverse effects stemming from prolonged immunosuppressive drug usage loom large over clinical transplantation. The maintenance of immune equilibrium and its post-transplantation reconfiguration stand as pivotal determinants of transplant outcomes and patient prognoses. Notably, the pursuit of immune tolerance induction presents discernible therapeutic advantages, encompassing a diminishment of the toxic ramifications linked to immunosuppressive agents and an enhancement of overall quality of life.

The targeted instigation of immune tolerance stands at the forefront of biomedical and scientific inquiry, closely aligned with significant clinical demand. The immune response provoked by organ transplantation exhibits multifaceted and variegated dimensions. Within distinct immune responses, whether of the acute or chronic variety, or mediated by cells or antibodies, immune cells within transplanted organ grafts, peripheral lymphoid organs, and peripheral blood manifest intricate and heterogeneous functionalities. An array of immune cell types and their subpopulations delineate disparate phenotypic traits and execute both immune-boosting and immune-suppressing roles, culminating in an intricate and delicately regulated immune milieu.

Delving into the vanguard issues associated with the orchestration of immune homeostasis and its remodeling in the context of organ transplantation necessitates, but is not confined to, a comprehensive delineation of the temporal and spatial features characterizing the dynamic alterations in systemic and localized immune responses before and after transplantation. Additionally, an in-depth exploration of the attributes exhibited by immune cells, molecular kinetics, and the principal regulatory networks underlying distinct forms of transplant rejection is indispensable.

By dissecting the temporal and spatial progression of dynamic changes and the remodeling of immune cells originating from both donors and recipients, alongside their correlation with prognostic indicators, the establishment of a diagnostic and treatment framework for immune tolerance induction and immune homeostasis remodeling becomes a paramount objective. Further, comprehending the chronological interplay between immune homeostasis regulation, remodeling, and the organism's capacity for anti-tumor and anti-infection immunity opens avenues for the development of pertinent diagnostic and therapeutic strategies.

A more nuanced comprehension of the distinctive attributes and clinical import associated with diverse immunosuppressive agents in the context of immune homeostasis and remodeling serves to guide judicious clinical regulation. The efficient and judicious reconstruction and upkeep of immune homeostasis post-organ transplantation carry the potential to markedly enhance the practical application of this therapeutic modality within clinical transplantation.

(6) Monoclonal antibody therapy for Alzheimer's disease

Alzheimer's disease (AD) is a neurodegenerative disease characterized by the insidious erosion of cognitive function and behavioral faculties. In the backdrop of a globally aging populace, it has burgeoned into one of the foremost afflictions exerting a substantial toll on both social and economic health across the world. The pathogenesis of Alzheimer's remains an intricate conundrum, its precise mechanistic underpinnings still eluding comprehensive elucidation. Currently, the amyloid cascade hypothesis, prominently featuring amyloid β-protein (Aβ), occupies a preeminent status in the pantheon of theories explicating the pathogenesis of AD. In accordance with this paradigm, three principal domains of pharmacological inquiry have emerged, revolving around the modulation of Aβ: the abatement of Aβ production, mitigation of Aβ aggregation, and fortification of Aβ clearance. Amongst these pursuits, passive immunotherapy aimed at augmenting Aβ clearance, specifically through the conduit of anti-Aβ humanized monoclonal antibody therapy, and has ascended to the vanguard.

Over the years, global pharmaceutical conglomerates have infused colossal financial investments into the realm of Alzheimer's disease therapeutics. Regrettably, the developmental trajectory has proven to be a vexing odyssey, fraught with perils, with the attrition rate surpassing that observed in other therapeutic domains. The overwhelming majority of these endeavors have culminated in disappointment, primarily stemming from safety concerns or an absence of cogent clinical efficacy substantiation. Notably, in the annals of 2021, the US Food and Drug Administration (FDA) granted accelerated approval to the human IgG1 monoclonal antibody Aducanumab, a move that transpired amidst contentious discourse.

In the subsequent year of 2022, the outcomes of Phase clinical trials assessing the efficacy of lecanemab, an antibody targeting Aβ oligomers, were unveiled. The year 2023 witnessed the FDA's imprimatur for lecanemab's market deployment. Notably, the results unveiled a 27% retardation in the advancement of early-stage disease, achieving the primary clinical endpoint alongside the full constellation of pivotal secondary endpoints. Furthermore, the incidence of treatment-associated adverse effects registered a notable decline. It is worth accentuating that lecanemab not only decelerates the inexorable progression of the malady but also engenders an amelioration in clinical symptomatology. While additional scrutiny concerning lecanemab's efficacy and safety remains incumbent, it undeniably furnishes a compelling exemplar fortifying the edifice of the Aβ hypothesis. It signifies one of the most momentous strides in the sphere of Alzheimer's disease therapeutics in recent memory.

Historically, therapeutic interventions for Alzheimer's disease predominantly fixated upon palliative measures bereft of the capacity to impede disease advancement. The affirmative findings stemming from the Phase clinical investigations of Lecanemab undeniably kindle newfound optimism among the global cohort of researchers, clinicians, and patients embroiled in Alzheimer's disease research. This harbors the potential to catalyze augmented investments within the domain of monoclonal antibody drugs for Alzheimer's disease, thereby affording succor to an expansive patient cohort and fostering the maturation of clinical diagnostic and therapeutic paradigms.

(7) Biomacromolecular phase separation and membraneless organelles

Cells harbor exceedingly intricate structural arrangements that orchestrate the meticulous and orchestrated execution of intricate biochemical processes. As such, a profound comprehension of the nuanced internal architectures of cells assumes paramount importance in unraveling the intricacies of cellular functions and regulatory pathways. Within eukaryotic cells, alongside membrane-bound organelles ensconced by phospholipid bilayers, a diverse array of membraneless organelles emerges through the spontaneous aggregation of biomacromolecules. These membraneless entities, characterized by their dynamic adaptability, exhibit alacrity in mounting responses and orchestrating a gamut of pivotal physiological functions, encompassing the regulation of transcription, translation, and signal transduction. Consequently, the exploration of the mechanisms underpinning membraneless organelles and their synergy with membrane-bound organelles to facilitate cellular compartmentalization stands as an emergent frontier and challenge within the life sciences.

Recent breakthroughs have laid bare the crux of the mechanism governing the genesis of membraneless organelles, which revolves around the phenomenon of phase separation propelled by polyvalent interactions among biomacromolecules. Interdisciplinary teams of scientists across the globe are actively embarked upon the exploration of novel membraneless organelles and their attendant physiological functions. This endeavor is underscored by an ardent quest to unravel the physicochemical attributes characterizing membraneless organelles and the intricacies of the dynamic processes governing their assembly, regulation, and eventual dissolution. It is noteworthy that aberrant phase separation precipitates a direct etiology in several formidable maladies, including but not confined to cancer and neurodegenerative disorders. In this context, scientists are vigorously probing strategies to intervene in anomalous phase separation, harboring the potential to furnish novel therapeutic modalities for diseases that currently elude effective treatment. Notably, Chinese scientists occupy a preeminent position on the global stage in the realms of phase separation and membraneless organelles.

Research endeavors dedicated to the exploration of biomolecular phase separation and the intricacies of membraneless organelles are poised to perpetuate their preeminence within the sphere of life sciences. The trajectory of these investigations will encompass a deeper penetration into the universal regulatory mechanisms and foundational tenets underpinning phase separation. This shall be paralleled by a profound delving into the labyrinthine intricacies underpinning cellular structure and function. Such efforts are anticipated to catalyze revolutionary waves within multifarious domains, spanning medicine, biotechnology, and the realm of pharmaceutical drug development.

(8) Research on the mechanism of organoid construction and development in primates

Organoids, self-organized three-dimensional tissue cultures derived from various stem cell types, have garnered increasing attention for their capacity to closely mimic *in vivo* tissue structures and functions. These miniature organ-like structures can be generated from a range of stem cell sources, including pluripotent stem cells (PSCs), induced pluripotent stem cells (iPSCs), embryonic stem cells (ESCs), adult stem cells (ASCs), and tumor cells. With established models for organs such as the brain, retina, lung, and liver, among others, organoids serve as invaluable tools for *in vitro* modeling of tissue morphogenesis, organogenesis, regenerative medicine, drug testing, toxicology screening, and disease modeling. Their unique attributes include high physiological fidelity, genetic stability, rapid growth, and a high culture success rate, offering advantages over traditional patient-derived tumor xenograft models. Moreover, their histological and gene expression profiles closely mirror those of native tissues, enhancing their clinical and scientific utility. Despite these advancements, challenges persist, including the lack of standardized culture conditions and the limited availability of samples. Future research should focus on integrating organoids with other advanced technologies to enhance research accuracy. In China, organoid research has been recognized as a pivotal area of innovation, featuring prominently in the 14th Five-Year Plan's national key research and development programs, where they are employed for disease modeling, target identification for diagnosis and treatment, and the exploration of new therapeutic strategies.

(9) The human pangenome and disease pangenome

Approximately two decades ago, the Human Genome Project embarked on a seminal endeavor, proposing a reference genome for the human species. Over time, as the corpus of whole-genome sequencing data expanded, a noteworthy observation surfaced: the existence of genome sequencing disparities among individuals, notably, the genomic diversity inherent to the human population. Evidently, the reference genome, painstakingly derived from a limited cohort of individuals, has struggled to satiate the burgeoning demands of genomic inquiries into various diseases. In response, the concept of the human pangenome has emerged. The pangenome, in essence, constitutes a compendium of DNA sequences that encapsulate genetic variants sourced from diverse individuals within a species or a gene pool that encompasses the entirety of said species.

Pangenomic investigations are underpinned by three fundamental components: core genes, distributed genes, and population-specific genes. Core genes are ubiquitous, shared across all individuals within a species, exemplified in the context of humans by genes universally present in every individual. These core genes exert a commanding influence over the foundational biological processes and phenotypic attributes characteristic of the species. In contradistinction, distributed genes, often termed non-essential genes, exhibit a presence in some individuals while remaining conspicuously absent in others. Concurrently, population-specific genes exclusively manifest within individuals belonging to distinct ethnic groups. While these distributed genes and population-specific genes may not be indispensable for the fundamental biological requisites of the species, they may prove to be integral in response to environmental pressures, thereby delineating or augmenting the species' capacity to secure a survival advantage.

Distinct from traditional genomic analysis, which primarily serves as a conduit for the identification of genetic mutations, pan-genome research endeavors to unearth hitherto undiscovered genetic constituents, encompassing expansive structural variants (SVs) and even novel presence-absence variations (PAVs) within the genetic repertoire. These variations have the potential to confer heightened susceptibility to specific diseases. On a global scale, this scientific pursuit has yielded remarkable outcomes, encompassing the delineation of a preliminary human pangenome reference and the assembly of a pangenome reference spanning 36 distinct Chinese ethnic minorities. Furthermore, Chinese researchers have pioneered the development of an automated pangenomic analysis pipeline (known as HUPAN) and culminated in the inaugural pangenomic analysis of gastric tumors specific to the Chinese population. Nevertheless, the field of pan-genomic research continues to grapple with certain technical bottlenecks. A nuanced exploration of the intricate relationship between novel genetic variants and their implications in human diseases mandates in-depth scrutiny and exploration.

(10) Mechanisms of chromatin dynamic modification on tissue and organ development

Dynamic chromatin modifications refer to chemical modifications that occur at the chromatin level, which can affect the regulation of gene expression. Common chromatin dynamic modifications include DNA methylation, histone modification, and non-coding RNA. Dynamic chromatin modifications play a crucial role in cell development, physiological adaptation, and disease occurrence and progression. They can regulate the expression patterns of genes, enabling cells to adapt to various environmental and physiological demands. Additionally, abnormal modifications of chromatin dynamics are closely related to the occurrence and development of various diseases, including cancer, neurological diseases, and cardiovascular diseases. At present, the impact of chromatin dynamic modifications on tissue and organ development can be categorized into four aspects. First, gene expression regulation, where chromatin dynamic modifications can alter chromatin structure, thereby affecting gene accessibility and transcriptional activity. Second, tissue specificity, where different cells and tissues exhibit differences in gene expression patterns, is partly due to chromatin dynamic modifications. Third, genome stability, as chromatin dynamic modifications, can protect the genome from damage caused by external environmental and internal factors. Finally, transcriptional regulation, such as dynamic chromatin modifications, can influence the binding specificity of transcription factors and other regulatory factors to regulate the transcriptional activity of genes. In recent years, with the use of emerging technologies and methods such as high-throughput sequencing, genome editing, and multi-omics technology, both domestic and international research on the mechanisms underlying the impact of chromatin dynamic modifications on tissue and organ development has achieved a deeper and more comprehensive understanding. These findings provide an important reference for investigating the mechanisms and functions of dynamic chromatin modifications, building systematic associations, and decoding epigenetic "association information".

1.2 Interpretations for three key engineering research fronts

1.2.1 Multi-omics traits of complex diseases

Complex diseases such as endocrine diseases, neurodegenerative diseases, and cancer are driven by a combination of multiple environmental and genetic factors. However, despite extensive research, the etiopathogenesis of these diseases remains largely unknown, leading to a lack of precise treatment. In the context of an aging population, the increasing prevalence of complex diseases is not only a personal health issue, but also a substantial burden on public health. Therefore, there is an urgent need to develop effective and personalized treatments based on novel drug targets and clinically relevant biomarkers. However, traditional analytical methods, such as epidemiological research and clinicopathological analysis, cannot easily differentiate the complex relationship between causes and effects, and suffer from selection bias. High-throughput sequencing technologies have emerged over the past decades. The research outcomes achieved using multi-omics technologies make them a promising approach for investigating complex diseases.

Multi-omics technology refers to a collection of high-throughput methods for assessing a large number of genomic, transcriptomic, proteomic, metabolomic, and microbiological traits from biological specimens. Recently, new omics dimensions have been investigated. A more comprehensive molecular atlas of diseases reveals insights beyond previous traditional genome-wide association studies (GWAS), especially variants in non-coding sequences and essential metabolic molecules in tumor progression. In addition, researchers are working on methods for integrating multi-omics data. A well-established example is the integration of genomic and expression data to identify genetic variants that influence expression levels, termed as expression quantitative trait loci (eQTL). In summary, taking full advantage of these multi-omics data and analytical techniques is essential to unravel the traits of complex diseases and to realize their clinical application.

Based on a deeper understanding of complex diseases, the application of multi-omics approaches in complex disease research is primarily reflected in two aspects: identification of predictive biomarkers and screening for therapeutic targets. On the one hand, multi-omics data strengthens the link between molecular data and specific diseases through differential analysis, which encourages the exploration of pathogenesis and regulatory factors in complex diseases. On the other hand, the integration of multi-omics data with clinical and epidemiological data can provide stronger evidence for specific molecular mechanisms and causal relationships between external factors and diseases. Currently, researchers are actively overcoming quantitative restrictions in multi-omics cohorts and addressing deficiencies in data standardization for multi-platform datasets. These efforts are aimed at early diagnosis and precise treatment.

In the engineering research front of "multi-omics traits of complex diseases", the top three countries with core papers published are the USA, China, and the UK. Among them, China accounts for 26.39% of the published papers and is one of the major countries in research on this topic (Table 1.2.1). In terms of collaboration networks among the main countries (Figure 1.2.1), there is strong collaboration among the top ten countries.

The top ten institutions with core papers published in "multi-omics traits of complex diseases" were from the USA, China, the UK, and Denmark. The top three institutions, Harvard University, Chinese Academy of Sciences, and University of California, San Diego (Table 1.2.2) were from the USA and China. The collaboration network among major institutions demonstrates the close collaboration among national research institutions (Figure 1.2.2).

According to the results of the above statistical analysis, China is now in a parallel trend with similar foreign research in the frontier of "multi-omics characteristics of complex diseases".

Exploring the multi-omics traits of complex diseases in depth is of great significance for precision treatment. The construction of high-quality cohorts serves as the foundation for investigating multi-omics traits. Standardized, large-sample, multicenter, spatiotemporally paired cohorts will provide extensive dimensions and a wide analytical space for subsequent research. At present, some institutions have established tissue-specific multi-omics databases through close international cooperation, further driving the progress of integrative multi-omics. Additionally, leveraging phenotypic data (e.g., imaging information) and developing experimental models *in vitro* and *in vivo* are both feasible approaches to overcome sample acquisition challenges for neurodegenerative diseases, such as Parkinson's disease and Alzheimer's disease. Furthermore, advanced genomics technologies, such as single-cell transcriptomics and spatial transcriptomics, have led to a deeper understanding of cellular subpopulations related to diseases. For multi-institutional cohorts and multidimensional omics data, employing network analysis and machine learning methods is a dependable approach. It further delineates complex disease networks and explores potential pathways, thus providing valuable insights. These new technologies and abundant multi-omics data will definitely help to improve the prevention, early detection, and treatment of complex diseases in the future. For details, see the development roadmap (Figure 1.2.3).

Table 1.2.1 Countries with the greatest output of core papers on "multi-omics traits of complex diseases"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	4 174	44.27	421 943	101.09	2018.5
2	China	2 488	26.39	196 360	78.92	2018.8
3	UK	1 082	11.48	108 847	100.60	2018.6
4	Germany	1 002	10.63	99 737	99.54	2018.7
5	Canada	616	6.53	65 952	107.06	2018.6
6	France	610	6.47	62 675	102.75	2018.5
7	Italy	554	5.88	49 721	89.75	2018.6
8	Netherlands	535	5.67	58 463	109.28	2018.6
9	Australia	517	5.48	46 441	89.83	2018.6
10	Spain	456	4.84	40 483	88.78	2018.6

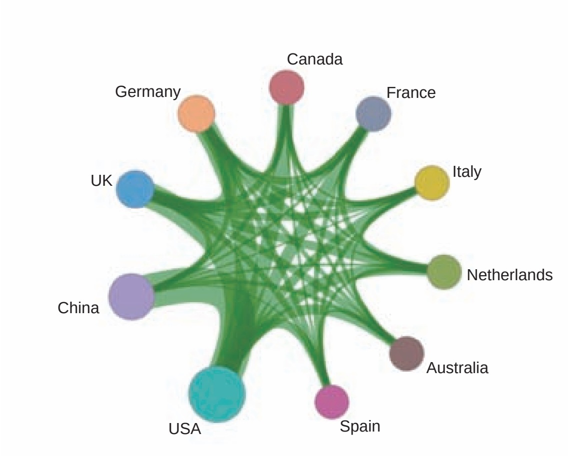

Figure 1.2.1 Cooperation network among major countries in the engineering research front of "multi-omics traits of complex diseases"

Table 1.2.2 Institutions with the greatest output of core papers on “multi-omics traits of complex diseases”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	495	5.25	65 133	131.58	2018.8
2	Chinese Academy of Sciences	438	4.65	40 153	91.67	2018.9
3	University of California, San Diego	248	2.63	32 491	131.01	2018.7
4	University of Copenhagen	226	2.40	25 923	114.70	2018.7
5	Stanford University	207	2.20	26 167	126.41	2018.9
6	University of Michigan	169	1.79	16 829	99.58	2018.8
7	Zhejiang University	166	1.76	13 933	83.93	2019.1
8	Baylor College of Medicine	165	1.75	23 176	140.46	2018.8
9	University of Pennsylvania	165	1.75	17 229	104.42	2018.7
10	Imperial College London	161	1.71	14 924	92.70	2018.6

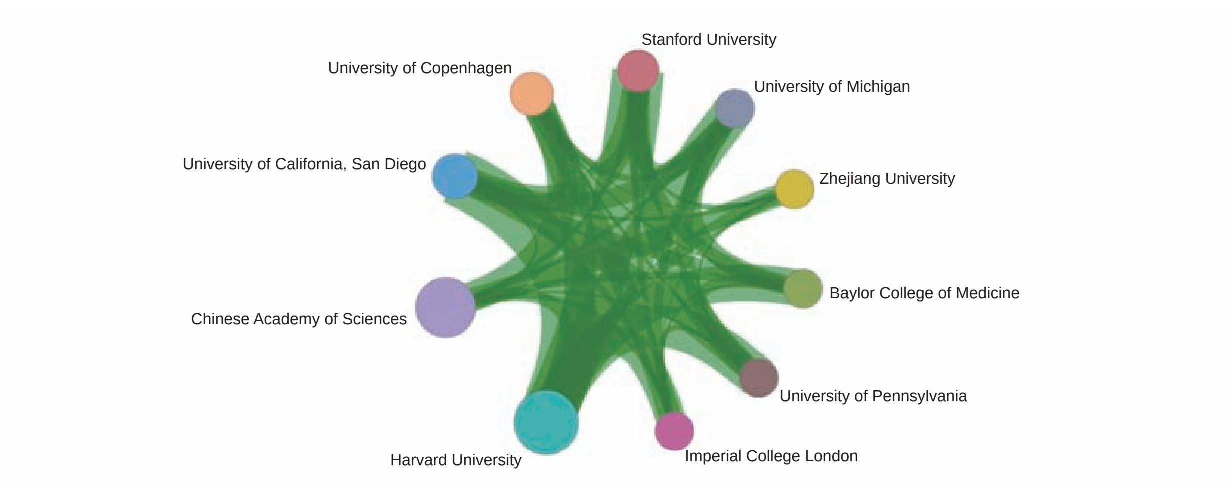

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “multi-omics traits of complex diseases”

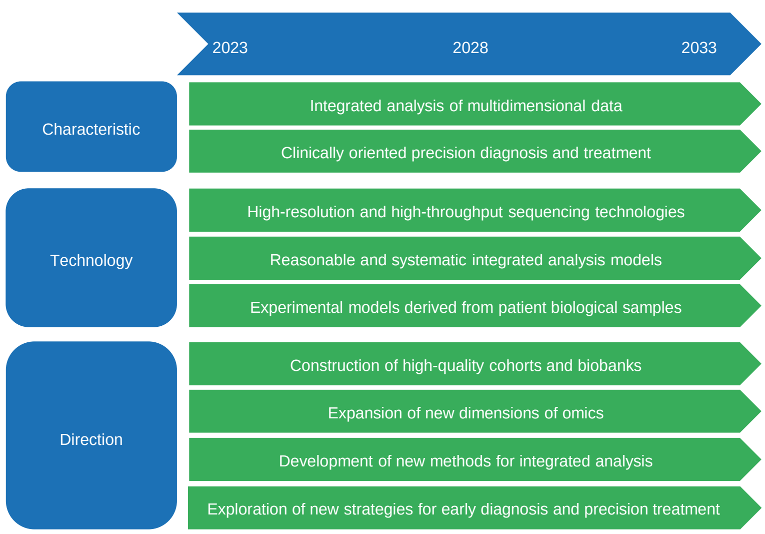

Figure 1.2.3 Roadmap of the engineering research front of “multi-omics traits of complex diseases”

1.2.2 Mechanism of persistent virus infection and reactivation and analysis of intervention targets

The outcome of viral infection is determined by the interaction between viral replication and the host defense system, which results in two types of clinical manifestations: acute infection and persistent infection. Multifarious viruses, such as human herpesviruses (e.g., herpes simplex virus, cytomegalovirus, Epstein-Barr virus), hepatitis B virus, human papillomavirus, human immunodeficiency virus, and hepatitis C virus, can establish persistent infections, making it a crucial area of focus in medical virology research. Viruses that are persistently infected can replicate continuously and produce progeny viruses, such as hepatitis C virus. Others have latent infections that can be reactivated under specific circumstances to produce progeny viruses, such as the herpes virus.

Two factors are required for the development of persistent viral infection: first, the virus suppresses its cytotoxic effects to prevent the death of infected host cells; second, the virus effectively evades host immune clearance, including innate and adaptive immunity, to continue replicating within host cells or remain latent within infected cells. When latent viruses in infected host cells enter the lytic phase, where they reproduce and disseminate once more, this is referred to as viral reactivation. The course of disease caused by persistent viral infection is mostly chronic or repeated, difficult to cure, and even can lead to the development of tumors or autoimmune diseases, seriously endangering human health and causing substantial economic burdens to society. The mechanism of persistent viral infection and reactivation is extraordinarily intricate, and an accurate understanding of the relevant mechanism can provide new targets and strategies for the prevention and treatment of related infectious diseases, not only improving the effectiveness of existing viral diseases treatment, but also providing strategic reserves to deal with future emerging viruses.

Research on the mechanisms of persistent viral infection is primarily concerned with the regulation of viral replication and immune modulation. Studies of viral replication regulation and reactivation mainly include the virus genome encoding product and its structure, function and regulatory mechanism, the maintenance mechanism of viral genome replication in host cells, the regulation mechanism of viral genome transcription and replication, the integration mechanism of viral genome, the transformation mechanism of virus-lytic infection, the mode of virus-induced host cell death and its regulatory mechanism, the carcinogenic mechanism of virus infection, host limiting factors and their mechanisms of action.

The study of viral replication regulation and reactivation mainly include the mechanism of restriction of viral antigen expression, the mechanism of viral antigen mutation, the mechanism of immune pardoning site infection, the mechanism of virus-induced immunosuppression, and the mechanism of acquired immune depletion such as T cells exhaustion. Intervention strategies for persistent viral infection can be divided into two broad categories: targeting viral replication and targeting virus-specific immune responses. Targeted virus replication strategies are mainly aimed at blocking specific stages of the virus life cycle, including targeting the virus itself or host factors required for virus replication. Targeting virus-specific immune responses is mainly about restoring the host’s effective immune response to eliminate viral infection.

Due to the continuous development of virology, immunology, molecular biology, cell biology and other disciplines, prominent progress has been made in resolving the mechanism of persistent viral infection and reactivation. For example, human immunodeficiency virus (HIV) can evade immunological surveillance through genome integration and high variability, leading to persistent infection of lymphoid system cells. Varicella-zoster virus (VZV) can establish a state of immune evasion in various specialized cells and the central nervous system, resulting in persistent infection of the nervous system. Hepatitis B virus (HBV) can trigger T cell exhaustion, leading to persistent infection. Targeted viral replication is the most commonly used intervention strategy for viral infection, which mainly includes antiviral compounds, interferon and therapeutic target cell modification. Intervention strategies targeting virus-specific immune responses have not yet been widely used in clinical practice, but broad-spectrum neutralizing antibodies, toll-like receptor agonists, and therapeutic vaccines have manifested encouraging preliminary results in animal models and clinical trials.

Currently, in the engineering research frontier of “mechanism of persistent virus infection and reactivation and analysis of intervention targets”, the top three countries with the highest number of core publications are the USA, China, and Germany (Table 1.2.3). Among them, China accounts for 34.33% of the core publications, making it one of the major countries in research of this front. From the perspective of collaboration networks among main countries (Figure 1.2.4), there is close cooperation among the top ten countries.

Table 1.2.3 Countries with the greatest output of core papers on “mechanism of persistent virus infection and reactivation and analysis of intervention targets”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	285	56.55	24 544	86.12	2018.2
2	China	173	34.33	12 280	70.98	2018.3
3	Germany	58	11.51	4 749	81.88	2018.6
4	UK	56	11.11	5 076	90.64	2018.7
5	France	51	10.12	4 369	85.67	2018.4
6	Canada	31	6.15	3 177	102.48	2018.0
7	Japan	26	5.16	1 515	58.27	2018.5
8	Australia	21	4.17	1 764	84.00	2018.6
9	Netherlands	18	3.57	1 397	77.61	2018.0
10	Belgium	16	3.17	1 087	67.94	2018.6

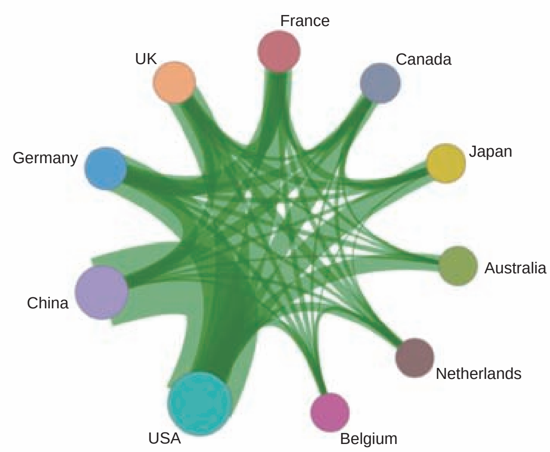

Figure 1.2.4 Cooperation network among major countries in the engineering research front of “mechanism of persistent virus infection and reactivation and analysis of intervention targets”

The top ten institutions with core papers published in the engineering research frontier of “mechanism of persistent virus infection and reactivation and analysis of intervention targets” were from the USA, China, and the UK. The top three institutions, including Harvard University, the US National Institute of Allergy and Infectious Diseases, and Chinese Academy of Sciences (Table 1.2.4) were from the USA and China. The collaboration network among major institutions (Figure 1.2.5) enunciates that there is strong cooperation among American scientific research institutions, and some cooperation among other institutions.

Based on the above statistical analysis results, China is currently in a parallel trend with similar foreign research in the frontier of “mechanism of persistent virus infection and reactivation and analysis of intervention targets”.

In-depth understanding of the mechanisms of persistent viral infection and reactivation urgently requires the strengthening of basic disciplines such as virology, immunology, molecular biology, and cell biology, as well as the development of cutting-edge biotechnologies and their deep integration with materials science and engineering technologies. This will greatly enhance our ability to decipher the mechanisms of persistent viral infection and reactivation, and enable the development of effective antiviral

Table 1.2.4 Institutions with the greatest output of core papers on “mechanism of persistent virus infection and reactivation and analysis of intervention targets”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard University	50	9.92	5 480	109.60	2018.3
2	National Institute of Allergy and Infectious Diseases	31	6.15	2 259	72.87	2018.5
3	Chinese Academy of Sciences	21	4.17	1 771	84.33	2018.4
4	Sun Yat-sen University	19	3.77	1 545	81.32	2018.2
5	University of Washington	18	3.57	2 472	137.33	2018.3
6	University of Pennsylvania	17	3.37	1 836	108.00	2018.4
7	University of California, San Francisco	16	3.17	1 646	102.88	2018.4
8	Chinese Academy of Agricultural Sciences	15	2.98	838	55.87	2018.9
9	Duke University	14	2.78	1 079	77.07	2018.4
10	University of Oxford	13	2.58	1 303	100.23	2018.9

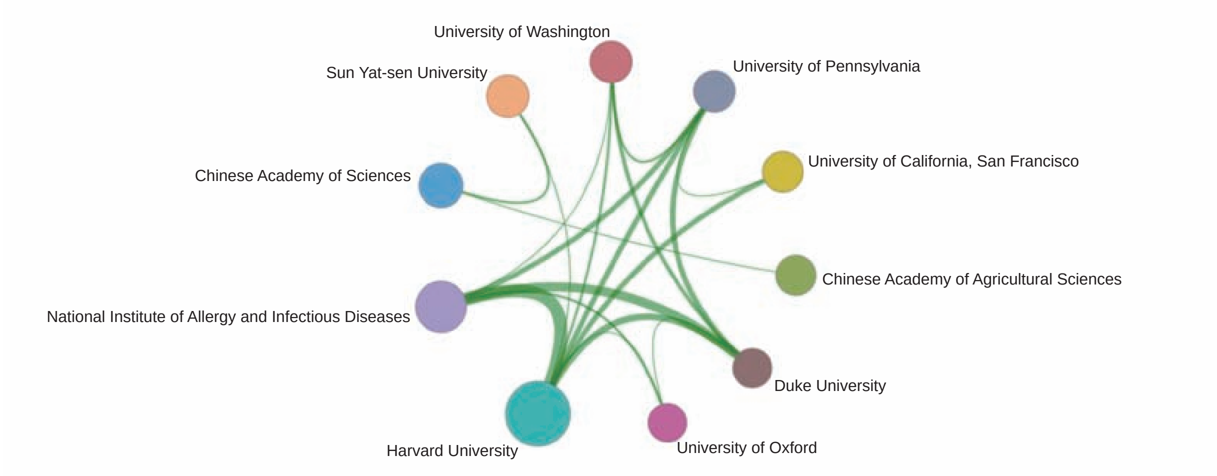

Figure 1.2.5 Cooperation network among major institutions in the engineering research front of “mechanism of persistent virus infection and reactivation and analysis of intervention targets”

drugs, immunotherapies, cell therapies, and new-generation vaccines, as well as effectively support the prevention, control, diagnosis, and treatment of chronic or major infectious diseases.

For a long time, the research on the mechanism of persistent viral infection and reactivation has predominantly been based on the study of individual viruses or host genes, single signaling pathways, and single intervention targets. This limited approach has led to an incomplete and shallow understanding of the mechanisms involved, and the translation of basic research findings into clinical practice has been challenging. To address this, a systems biology approach is needed, utilizing new technologies such as multi-omics, artificial intelligence, and high-throughput screening, to provide a panoramic, dynamic, multi-scale, and multidimensional elucidation of the relevant mechanisms. The lack of suitable cell and animal models has also hindered the exploration of these mechanisms. The emergence of technologies such as organoids and humanized animal models can provide new research platforms to overcome these limitations.

In terms of intervention strategies, gene editing technology has been successfully applied to target a variety of viral genomes.

However, challenges still exist in terms of targeting efficiency, off-target effects, delivery platforms, and viral escape mutations. The research and development of therapeutic vaccines should be closely combined with material science and engineering technology to achieve breakthroughs in antigen design, delivery system, adjuvant development and other key aspects. Targeted blocking of immune checkpoints has shown some potential in combating HIV infection, but the selection of biomarkers, the development of drug resistance, and potential adverse reactions are pressing issues that need to be addressed. Multiple studies have shown that adoptive T-cell therapy is effective in clearing viral infections and enhancing antiviral immunity after stem cell transplantation. It has demonstrated promising prospects in preclinical studies for treating respiratory viruses or immunodeficiency viruses, and the indications for such therapies are expected to expand gradually. However, the safety and efficacy of these therapies still need further validation (Figure 1.2.6).

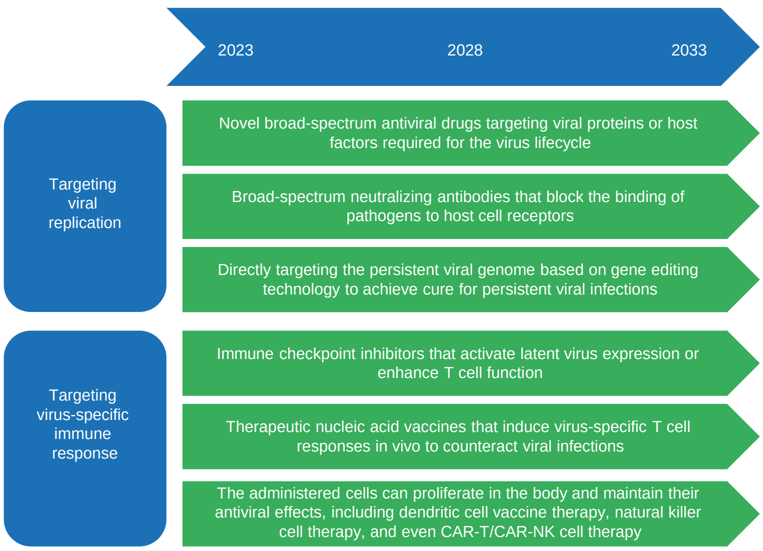

Figure 1.2.6 Roadmap of the engineering research front of “mechanism of persistent virus infection and reactivation and analysis of intervention targets”

1.2.3 The core human microbiome and host−microbiome interaction

The microbiome plays a crucial role in maintaining human health by participating in various physiological processes such as nutrient metabolism, immune regulation, inflammatory responses, and endocrine regulation. The identification of a universal signature of a healthy or unhealthy human microbiome is essential for maintaining a healthy status and preventing chronic diseases. However, due to the large inter-individual variation in human microbiota and the complex interplay between the microbiota and their host, the core human microbiome is yet to be defined.

The core human microbiome refers to the microbiota that is commonly shared among individuals and has significant impacts on human health. Despite the popularity of this term and its growing use, there is a lack of consensus on how a core microbiome should be quantified in practice. Therefore, identification of the core human microbiota and microbiome-targeting therapy represents a crucial frontier in medicine and healthcare enterprises.

To address these issues, researchers have initiated several large-scale, well-phenotyped cohorts to characterize the composition and function of the human microbiota in recent years. There are several landmark human microbiome projects, such as the US National Institutes of Health-funded Human Microbiome Project (HMP) and Dutch Microbiome Project (DMP). These projects mapped the human microbiome in their populations and revealed comprehensive profiles of microbiome compositions and functions using multi-omics data, such as metagenomics, metatranscriptomics, and metabolomics. They also explored the associations of microbial features with the host exposome and diverse diseases to clarify the contributions of host intrinsic factors, modifiable environmental factors, and health-related factors in shaping the human microbiome. To further disentangle meaningful host-microbiota interactions, they integrated human genetics data, leveraged longitudinal data, and utilized in silico mediation analyses to reveal putative causal relationships between the microbiome and their host phenome. To identify potential therapeutic targets for microbiota-directed intervention, experiments using gnotobiotic mice or piglets have been conducted to validate computationally identified targets and further confirm the mechanism underlying microbiota-host interactions. Together, these efforts provide a rich resource for dissecting the link between the human microbiome and health, thereby pinpointing future directions for microbiome-directed interventions.

However, the majority of clinical trials on microbiota-targeted interventions have reported a lack of efficacy. There are several reasons for this finding. First, the quantification of the core human microbiome in prior research primarily relies on abundance-based indicators, which may potentially overlook microorganisms that are ecologically and functionally significant. Second, existing studies investigating the microbiota-host relationship extensively rely on small-scale population studies or animal models. Although these small studies provide valuable insights, they may not fully capture the complexities and variations in larger human populations. Meanwhile, the biological differences between animals and humans can also limit the translation of findings from animal models towards humans; Thirdly, it is important to note that current sequencing technology and analysis methods have limitations in inferring causations from microbiome data; Lastly, due to substantial differences in diet, lifestyle and ethnicity, conclusions drawn from certain population may not be generalizable to other populations.

In the engineering research front of “the core human microbiome and host–microbiome interaction”, the top three countries with core papers published are the USA, China, and France (Table 1.2.5). Among them, China’s core papers account for 28.05%, making it one of the main research countries in this front. According to the cooperation network among major countries (Figure 1.2.7), the top ten countries in the number of core papers have close cooperative relationships.

In the engineering research frontier of “the core human microbiome and host–microbiome interaction”, the top ten institutions with the highest number of core papers were principally from the USA and European countries. The top three institutions, Harvard University, University of California, San Diego, and Wageningen University & Research, were from the USA and the Netherlands (Table 1.2.6). The collaboration network among the major institutions demonstrates that some institutions have cooperative relationships (Figure 1.2.8).

Therefore, there are several major challenges in human microbiome research, including identifying the core human microbiome, deciphering its role in regulating host physiology and pathology, and identifying microbiome-targeting therapies. To address these challenges, the development of a new framework and the incorporation of new technologies are crucial. We espouse the adoption of a multifaceted strategy, integrating diverse layers of omics data, which encompass comprehensive genome sequencing, single-cell sequencing, high-throughput culturomics, and longitudinal data analysis. This integrative approach is pivotal in fostering a deeper comprehension of causative inferences and mechanistic insights within the domain. Furthermore, the refinement of computational methodologies is indispensable, as it will facilitate the harmonious amalgamation of multi-omics data, thereby elucidating plausible mechanisms and pinpointing molecular targets for therapeutic intervention. Furthermore, we underscore the critical need to optimize the design of research studies, effectively expand microbiome inquiries within epidemiological populations, and ensure the reproducibility of translational outcomes. Lastly, we accentuate the urgency of incorporating innovative organ-on-chip technologies, as they hold the potential to enable comprehensive investigations into the interactions between the microbiome and the human organism. The synergistic integration of these approaches shall expedite the discovery of microbiota-related biomarkers and transition microbiome research from the realm of association to causality. Ultimately, this endeavor shall facilitate the design of robust therapeutic interventions aimed at modulating the composition of the gut microbiome.

In light of the aforementioned statistical analyses, it becomes evident that China is aligned with international trends in the research frontier concerning “the core human microbiome and host–microbiome interaction”. To harness the distinct advantages

Table 1.2.5 Countries with the greatest output of core papers on “the core human microbiome and host−microbiome interaction”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	33	40.24	2 980	90.30	2018.7
2	China	23	28.05	2 065	89.78	2018.8
3	France	15	18.29	1 925	128.33	2018.7
4	UK	15	18.29	1 730	115.33	2018.8
5	Australia	13	15.85	1 605	123.46	2018.6
6	Germany	10	12.20	1 511	151.10	2018.8
7	Canada	10	12.20	1 370	137.00	2019.0
8	Netherlands	9	10.98	1 343	149.22	2019.4
9	Italy	8	9.76	702	87.75	2018.6
10	India	5	6.10	895	179.00	2019.2

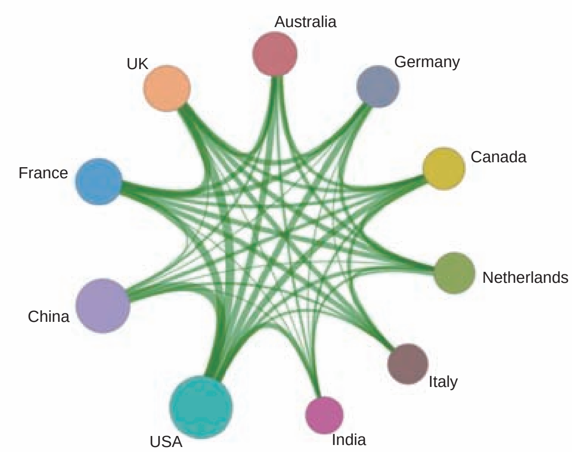

Figure 1.2.7 Cooperation network among major countries in the engineering research front of “the core human microbiome and host−microbiome interaction”

Table 1.2.6 Institutions with the greatest output of core papers on “the core human microbiome and host−microbiome interaction”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Harvard university	5	6.10	279	55.80	2019.6
2	University of California, San Diego	4	4.88	359	89.75	2019.2
3	Wageningen University & Research	3	3.66	996	332.00	2019.3
4	University of Minnesota	3	3.66	759	253.00	2019.0
5	University College Cork	3	3.66	534	178.00	2019.7
6	University of Kiel	3	3.66	400	133.33	2017.0
7	University of Helsinki	3	3.66	397	132.33	2019.0
8	King’s College London	3	3.66	227	75.67	2019.3
9	University of Munich	3	3.66	222	74.00	2019.7
10	University of New South Wales	3	3.66	217	72.33	2018.7

of the Chinese populace, it is important to further exploit these resources. A high-caliber resource platform, centered on the human microbiome, should be established, concurrently with the meticulous delineation of microbiome maps specific to the Chinese population. This concerted effort is poised to comprehensively characterize the composition and functional attributes of the core microbiome within the Chinese demographic landscape.

These innovative strategies related to human microbiome research include but are not limited to fecal microbiota transplantation, engineered living biotherapeutics based on probiotics, prebiotics, and targeted nutritional interventions. Additionally, integrating host genetic information may also aid in the identification of key genetic loci that interact with the core human microbiome, facilitating the discovery of the core microbiota underlying disease pathogenesis. Consequently, this may propel the advancement of microbiome-based precision medicine, including the development of personalized probiotics, prebiotics, and postbiotics. These future directions are highlighted in the development roadmap of the project "core human microbiome and host−microbiome interaction" (Figure 1.2.9). In summary, it is necessary to continuously propel the development of technology, optimize intervention strategies targeting core microbial communities, and strengthen international cooperation and communication to identify the core microbiome that is responsible for maintaining host homeostasis.

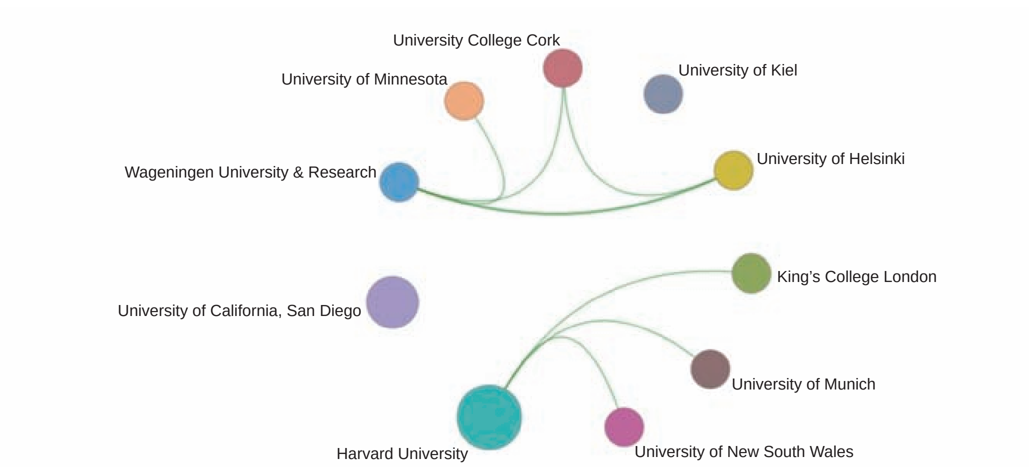

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of "the core human microbiome and host−microbiome interaction"

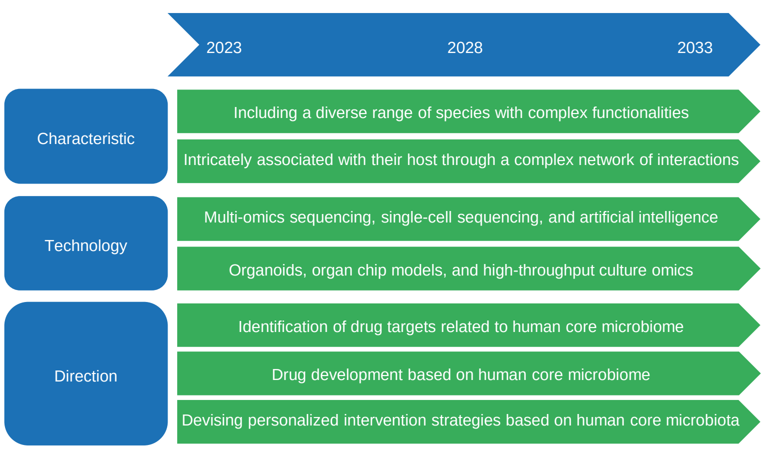

Figure 1.2.9 Roadmap of the engineering research front of "the core human microbiome and host−microbiome interaction"

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

This section of the review describes the Top 10 engineering development fronts in the field of medicine and health, including basic medicine, clinical medicine, pharmacy, traditional Chinese medicine, medical informatics, and biomedical engineering (Table 2.1.1). The emerging fronts are “T-cell receptor-engineered T-cell therapy”, “single-cell spatial transcriptomics technology”, “chimeric antigen receptor natural killer cell therapy”, “single-molecule protein sequencing”, “the application of a large language model in digital healthcare”, and “epigenetic editing technology”. Traditional research has focused on “combining antibody-drug conjugates with immunotherapy for malignancies”, “application of medical nanorobots in cancer treatment”, “technologies for synthetic immunology”, and “small nucleic acid drugs”. All patents related to these 10 fronts, published between 2017 and 2022, are listed in Table 2.1.2.

Table 2.1.1 Top 10 engineering development fronts in medicine and health

No.	Engineering development fronts	Published patents	Citations	Citations per patent	Mean year
1	T cell receptor engineered T cell therapy	429	1 447	3.37	2020.2
2	Combining antibody-drug conjugates with immunotherapy for malignancies	334	1 815	5.43	2019.9
3	Single-cell spatial transcriptomics technology	162	942	5.81	2020.4
4	Chimeric antigen receptor natural killer cell therapy	332	829	2.50	2020.5
5	Application of medical nanorobots in cancer treatment	2 505	5 842	2.33	2020.3
6	Technologies for synthetic immunology	431	726	1.68	2019.6
7	Small nucleic acid drugs	1 723	3 078	1.79	2019.8
8	Single-molecule protein sequencing	398	2 302	5.78	2019.7
9	The application of large language model in digital healthcare	2 042	7 062	3.46	2020.7
10	Epigenetic editing technology	97	552	5.69	2020.2

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in medicine and health

No.	Engineering development fronts	2017	2018	2019	2020	2021	2022
1	T cell receptor engineered T cell therapy	23	31	83	86	101	105
2	Combining antibody-drug conjugates with immunotherapy for malignancies	44	44	35	59	74	78
3	Single-cell spatial transcriptomics technology	13	8	21	27	38	55
4	Chimeric antigen receptor natural killer cell therapy	14	25	35	62	87	109
5	Application of medical nanorobots in cancer treatment	227	221	276	426	679	676
6	Technologies for synthetic immunology	63	73	72	57	86	80
7	Small nucleic acid drugs	239	241	271	301	299	372
8	Single-molecule protein sequencing	54	56	56	76	89	67
9	The application of large language model in digital healthcare	62	99	203	355	630	693
10	Epigenetic editing technology	9	6	22	7	28	25

(1) T cell receptor engineered T cell therapy

T-cell receptor-engineered T-cell therapy (TCR-T) represents a novel cellular immunotherapy modality that entails the modification of T lymphocytes through the introduction of exogenous TCRs with the specific capacity to recognize the antigenic peptide-major histocompatibility complex (pMHC) displayed on tumor cells. This strategic alteration redirects T cells to mount targeted immune responses against malignancies. In 2002, the pioneering work of Rosenberg's group unveiled a seminal discovery: tumor-infiltrating lymphocytes (TILs) could selectively eliminate tumor cells following *in vitro* expansion and infusion. However, TILs pose accessibility limitations for various tumor types and necessitate prolonged cultivation to obtain clinically relevant quantities. Consequently, researchers embarked on the exploration of whether ordinary peripheral blood lymphocytes (PBLs) could be genetically engineered with TCR genes to combat tumors. This quest culminated in 2006 when Rosenberg's group demonstrated the clinical efficacy of genetically modified TCR-T cells in the context of melanoma, marking the inaugural proof of concept for TCR-T immunotherapy. Over more than two decades of rapid evolution, TCR-T immunotherapy has garnered global adoption for evaluating its clinical potential in the realm of solid tumors, exhibiting promising efficacy in clinical trials. Nevertheless, numerous challenges persist in engineering TCR-T cells with the requisite affinity and functionality to eliminate tumors and forestall recurrences. These hurdles encompass the selection of target antigens, evasion mechanisms employed by tumors to evade immune responses, concerns regarding off-target effects and safety, T cell unresponsiveness, and the phenomenon of T cell exhaustion. Conquering these challenges stands as a pivotal prerequisite for the realization of clinical success in TCR-T immunotherapy. Furthermore, a landmark achievement was reached in 2022 with the FDA's approval of Kimmtrak, a bispecific T-cell junction product developed by Immunocore. This regulatory endorsement marks a significant breakthrough in the field of TCR therapy, underscoring its growing prominence in the ongoing battle against cancer. Therefore, despite persistent barriers in TCR-T cell therapy, it is conceivable that ongoing scientific research and technological advancements will usher in novel breakthroughs, further advancing the frontiers of cancer treatment.

(2) Combining antibody-drug conjugates with immunotherapy for malignancies

Antibody-drug conjugates (ADCs) are composed of three units: ① an antibody that is selectively targeted to the tumor microenvironment, ② a linker that connects the antibody to the conjugate, and ③ a drug that exerts anti-tumor activity as a payload. A typical ADC has a small-molecule cytotoxic drug as the payload and a monoclonal antibody as the targeting moiety, which can specifically bind to tumor-associated antigens. This enables the conjugate to attack cancer cells precisely, with minimal harm to normal cells. To date, 15 ADC products have been approved and marketed worldwide, including six for hematological malignancies and nine for solid tumors, directed to CD33, CD30, CD22, CD79b, HER2, Nectin-4, Trop-2, BCMA, EGFR, CD19, and TF. Among them, five have been put on the market in China.As researchers make attempts to use a variety of drugs as the payload in ADCs, the concept of "antibody-everything conjugates" has been put forward. The payloads of ADCs can be generalized to include non-cytotoxic small-molecule drugs, cytokines, enzymes, oligonucleotides, bacterial exotoxins, biopolymers, radionuclides, and photosensitizers. For the antibody unit, the targeting moiety can also be nano-antibodies, bispecific antibodies, etc. in addition to the classical monoclonal antibodies. In recent years, it has been found that classical cytotoxic ADCs can mediate immunogenic cell death, thereby increasing the immunogenicity of tumor tissues and promoting the intratumoral recruitment of immune cells to kill "cold tumors". Based on this, it is believed that cytotoxic ADCs can be combined with tumor immunotherapies to manage malignancies. Furthermore, when an immunomodulatory drug is used as the payload, such an ADC can directly treat malignancies by modulating the immunity against tumors.

(3) Single-cell spatial transcriptomics technology

With the advent of the era of precision medicine, single-cell multi-omics technology is driving the studies of cancer, developmental biology, microbiology, immunology, and neuroscience, gradually becoming the focus of various disciplines of life sciences. However, during the process of cell dissociation, conventional single-cell sequencing technologies inevitably lose information regarding the spatial organization of cells essential for the functionality of complex tissue organs. This caveat can be overcome by single-cell spatial transcriptomics technology, which not only obtains transcriptome profiles of individual cells, but also locates the three-dimensional ordinates of transcripts and the cells expressing them. This, in turn, allows for the restoration of the architecture of the cell-type distribution and the internal operation of cell-to-cell communication between discrete cell subpopulations in different environments and organ systems. In 2020, single-cell spatial transcriptomics technology was named the technology of the year by *Nature Methods*, illustrating the enormous potential that this new technology. In the future, single-cell spatial transcriptomics technology will be able to change the understanding of complex tissues in various research fields. In particular, comparative studies of diseased and healthy tissues using single-cell spatial transcriptomics technology will prove useful in improving patient prognosis, optimizing therapeutic strategies, and uncovering potential therapeutic targets.

(4) Chimeric antigen receptor natural killer cell therapy

Chimeric antigen receptor natural killer (CAR-NK) cell therapy embodies an innovative cellular immunotherapy strategy wherein natural killer (NK) cells undergo genetic engineering with chimeric antigen receptor (CAR) genes, conferring upon them the capacity to selectively recognize and target tumor cells. These genetically modified NK cells undergo ex vivo expansion and are subsequently administered to patients to exert therapeutic effects in the context of cancer treatment. The genetic blueprint of the chimeric antigen receptor encompasses extracellular domains, including CARs (or NKR/TCR), facilitating precise tumor cell targeting, transmembrane domains, and intracellular signaling domains. Furthermore, functional components aimed at bolstering cell survival, promoting immune cell infiltration, and conferring resistance to the tumor microenvironment can be integrated into NK cells using viral or non-viral delivery systems. Following rigorous *in vitro* expansion and cultivation, CAR-NK cells are introduced into patients. CAR-NK cell therapy primarily finds its application in the domain of cancer treatment but extends its utility to clinical therapies for autoimmune conditions, infectious diseases, and age-related ailments. NK cells, recognized as “natural killers” of tumor cells within the body, offer inherent advantages in terms of safety, versatility, and off-the-shelf availability. They originate from diverse sources and offer cost-effective solutions, presenting considerable promise for the treatment of solid tumors. These inherent advantages position CAR-NK cell therapy as a promising avenue for broad application and industrial-scale production, thereby offering an expansive market outlook. A multitude of ongoing clinical trials focused on CAR-NK cell therapy attest to its safety and efficacy. This has garnered the attention of international stakeholders, propelling intensified research and development efforts within the NK cell arena and fostering the sustained expansion of the global market. Presently, immunotherapy encounters challenges in precisely and controllably regulating the *in vivo* activity of immune cells. Therefore, the application of synthetic biology techniques to CAR-NK cell immunotherapy, encompassing logic circuits, feedback mechanisms, intelligent control systems, and related technologies, facilitates quantitative, controlled, and scalable manipulation of NK cell functions. This groundbreaking approach yields intelligent CAR-NK cell therapeutics, characterized by their “living” nature, manipulability, and intelligence as synthetic immune cell drugs. This scalable and industrialized methodology surmounts existing limitations in immunotherapy effectiveness and holds potential for application in the treatment of major diseases, ultimately shaping the future of immunotherapy.

(5) Application of medical nanorobots in cancer treatment

An injectable medical antitumor nanorobot is a cutting-edge nanoscale functional assembly created by sophisticated nanofabrication techniques and applied for precise tumor localization, diagnosis, and treatment *in vivo* via intravenous injection. Nanorobots are typically fabricated from nanoscale biological materials that have undergone chemical and biological modifications to enhance their functionality. It can be effectively powered and controlled using various energy sources, including blood flow, chemical energy, magnetic fields, light waves, acoustic energy, and bioenergy. Moreover, nanorobots can sense and respond to pathological and physiological stimuli in the tumor microenvironment, which enables them to activate or deactivate specific functions, such as the controlled release of medications. Medical nanorobots hold vast application potential for cancer treatment, encompassing tumor monitoring, diagnosis, tumor microenvironment regulation, and comprehensive tumor therapy. Currently, the development of medical nanorobots is still in its infancy and faces several challenges. Key technical obstacles that must be addressed for clinical applications include scaling up the production of these nanorobots, ensuring their biosafety once injected into the body, and resolving the complexities of autonomous navigation and precise control within the bloodstream. Despite these technical challenges, medical nanorobots demonstrate immense potential, representing the future of precise drug delivery. They are expected to provide more accurate and personalized treatment for cancer patients, improve therapeutic efficacy, and prolong patient survival. The field is set to evolve in several key aspects: diversifying functionalities, enhancing intelligent driving mechanisms, and incorporating biodegradable materials. Furthermore, the integration of medical nanorobots with emerging technologies such as artificial intelligence and machine learning could further allow autonomous decision-making and self-optimizing treatment plans. As a novel approach to combat tumors, these nanorobots are anticipated to address some critical issues of traditional cancer treatments, such as low response rates, poor prognoses, and/or drug resistance.

(6) Technologies for synthetic immunology

Currently, the effectiveness of immunotherapy in the treatment of most tumors, especially solid tumors, is limited. Therefore, it is crucial to make significant advancements in the associated technologies and approaches. Additionally, traditional immunological engineering has evolved into the synthetic biology stage, giving rise to Synthetic Immunology, a novel discipline that combines basic immunology with modern synthetic biological technologies. Synthetic Immunology focuses on various major diseases such as tumors, autoimmune diseases, viral infections, and organ transplantation. By utilizing functional units/modules of immune molecules, cells, or systems, Synthetic Immunology employs binary systems and logical circuits for calculations. It designs and constructs logical gates, switches, feedback loops, oscillators, and other functional modules, forming synthetic immunological circuits that enable logical calculations to generate intelligent, controllable, more effective, and less toxic immune responses, thereby promoting the safety and efficacy of immunotherapy. The goal of Synthetic Immunology is to develop, scale up, and industrialize immunotherapy strategies against major diseases. It achieves this by renormalizing, redirecting, and reconstituting the host immune system through predictable, quantifiable, regulatable, and programmable rational designs. Advancements in Synthetic Immunology have significantly contributed to the development of modern immunotherapy theories, technologies, and products for the treatment of major diseases. In the future, there will be a demand for improved gene delivery capabilities to facilitate the design and application of synthetic immune cells with more complex gene circuits and enhanced intelligence.

(7) Small nucleic acid drugs

Small nucleic acid drugs refer to drugs can specifically silence the expression of disease genes using small nucleic acid molecules such as antisense oligonucleotides (ASOs), small interfering RNAs (siRNAs), and microRNAs (miRNAs) to cure specific diseases. These include ASOs, siRNAs, miRNAs, small activating RNAs (saRNAs), messenger RNAs (mRNAs), and RNA aptamers. The biggest challenge in the development of small nucleic acid drugs is to ensure that the drug stays in the body long enough and enters the targeted cells accurately to exert therapeutic effects while minimizing damage to normal cells after injection into patients. These problems can be solved by chemical modification and delivery systems to make nucleic acid drugs effective. The advantage of small nucleic acid drugs is their specificity in targeting multiple genes to treat diseases, thereby interfering with cell proliferation, angiogenesis, metastasis, and chemotherapy resistance. These advantages have led to the development of small nucleic acid drugs for a variety of diseases, including tumors, rare diseases such as amyotrophic lateral sclerosis, Duchenne muscular dystrophy, spinal muscular atrophy, viral diseases, kidney diseases, and cardiovascular diseases. The first small nucleic acid drug was launched in 1998, and currently, there are more than ten small nucleic acid drugs on the market worldwide, with about 80% launched after 2015. From the perspective of indications, most small nucleic acid drugs on the market are for genetic diseases. Compared with existing small molecule and antibody drugs, small nucleic acid drugs have the advantages of fast target screening, high R&D success rate, low drug resistance, broader treatment areas, long-lasting effects, and great development potential. In the future, with continuous breakthroughs and innovations in the application and technical fields of small nucleic acid drugs, the market demand and scale will continue to expand, and small nucleic acid drugs will have a broader development space.

(8) Single-molecule protein sequencing

Single-molecule protein sequencing is a technique for measuring the amino acid sequences that make up proteins at the single-molecule level. Protein sequencing presents a greater challenge than nucleic acid sequencing; proteins are complex and composed of 20 natural amino acids (in contrast, DNA molecules are formed from four nucleotides). Some proteins are only a few molecules in the cell, and for proteins, there are no similar techniques, such as nucleic acid amplification, making it difficult to detect low-abundance proteins. Protein sequencing studies are of great significance for the prediction of protein structure, detection of diseases, and development of protein drugs. The realization of single-molecule protein sequencing technology will bring new opportunities to proteomic research, digital biology, disease diagnosis, and medical development. Because proteins can provide profound information about health and disease, research on single-molecule protein sequencing technology has received much interest, and significant advances have been made in single-molecule protein sequencing methods based on fluorosequencing and nanopore technology, such as the optical protein sequencing chip by Quantum-Si and single amino acid identification in nanopores. Technologies with better spatiotemporal resolution, high-throughput sequencing methods, and more accurate and rapid signal analysis algorithms will be key to promoting major breakthroughs in single-molecule protein sequencing. The deep integration of single-molecule protein sequencing and proteomics, medical research, and artificial intelligence will bring new progress for the analysis of protein structure, early diagnosis of diseases, and development of biological drugs, while promoting the development of single-molecule protein sequencing into a convenient and rapid biotechnology with diversified application scenarios in the future.

(9) The application of large language model in digital healthcare

Large language models (LLMs) refer to language models trained on large-scale textual corpora that contain billions of levels (or more) of parameters, aimed at understanding and generating human language. They are trained on a large amount of text data and can perform a wide range of tasks, such as text summarization, translation, and sentiment analysis, among which GPT-4 is the most popular. LLMs include three main steps when processing input data: first, word embedding and converting words into high-dimensional vector representations, and then passing the data through multiple transformer layers. Finally, after being processed by the transformer layer, the model predicts the next most likely word or marker in the sequence based on the context to generate text. LLMs have a powerful ability to understand and generate text, making them stand out in the rapid development of modern medicine. In improving the level of medical diagnosis and treatment, LLMs help clinical doctors standardize the textual data generated during the diagnosis and treatment process and provide more accurate medical diagnosis and personalized treatment suggestions. In the field of medical image-assisted diagnosis, LLMs help radiologists interpret medical images, generate structured descriptive reports with standardized formats and language, and improve the quality and efficiency of image data management and deep mining. In promoting new drug research and development, LLMs assist clinical researchers in developing new treatment methods and drugs, identifying potential drug targets, and predicting drug side effects by achieving the largest global database-level literature review and meta-analysis. In terms of patient health management, LLMs combine individual genes, medical history, lifestyle habits, and other information to intelligently provide personalized medical and health management advice, helping people better prevent and self-manage chronic diseases. It can be foreseen that the future prospects of LLMs in the field of digital healthcare are full of hope. Although there are still challenges in ethical governance, data security, and human-machine collaboration, with the gradual maturity of the digital healthcare ecosystem and the intergenerational leap of artificial intelligence technology, the integration of LLMs and medical professional knowledge will completely change the traditional medical service model, giving new meaning and connotation to intelligent medical analysis and decision-making.

(10) Epigenetic editing technology

Epigenetic editing (EE) is a technology that precisely regulates the expression of target genes by altering epigenetic markers, such as DNA methylation and histone modification, without changing the genome sequence. This technology maintains the high specificity of traditional gene-editing tools while avoiding the potential genetic risks associated with DNA damage. Epigenetic editing technology can also simultaneously edit multiple targets to achieve precise and highly controlled adjustments, making it widely applicable in the treatment of complex polygenic diseases and personalized therapy. With the accumulation of non-clinical research data on epigenetic editing technology and the development and maturation of nucleic acid drug delivery systems, this technology will gradually move into the clinical stage, providing new treatment options for patients with complex diseases such as cancer, diabetes, viral infections, and autoimmune diseases. Based on the broad prospects of epigenetic editing technology in the field of disease treatment, China and developed countries in Europe and the USA attach great importance to research and development investments in this technology. At present, the research and development of epigenetic editing therapeutic drugs have achieved initial results, and many companies have disclosed preclinical research data. The development of high-precision and diverse epigenetic editing toolboxes, safe and efficient nucleic acid drug delivery systems, and large-scale production of nucleic acid drugs will be key to the future clinical transformation of epigenetic editing technology. The deep integration of epigenetic editing technology with epigenomics, organic chemistry, nanoscience, and artificial intelligence technology will provide new ideas for the optimization of epigenetic editing tools and the development of delivery systems, bringing great benefits to the treatment of many diseases.

2.2 Interpretations for three key engineering development fronts

2.2.1 T cell receptor engineered T cell therapy

T-cell receptor-engineered T-cell therapy (TCR-T) is a new type of cellular immunotherapy. A TCR gene that can specifically recognize tumor antigens is transfected into the patient's own T cells to express specific exogenous TCRs. The CD3 molecule transmembrane region on the T cell membrane is connected to the transmembrane region of the two chains of TCR through a salt bridge to form a TCR-CD3 complex, which effectively recognizes and binds to pMHC, thereby generating the first signal to activate T cells and forming an immune synapse with the participation of other cooperative signaling molecules to promote T cells. Cell division and differentiation further guide T-cells to kill injured and diseased cells.

TCR-T can recognize extracellular antigens, membrane antigens, and intracellular antigens, thus can recognize over 90% of antigens. Cancer is one of the leading causes of death worldwide and an important public health issue. Data show that there are currently an estimated 18.1 million new cancer cases and 9.6 million cancer deaths. The three traditional treatment methods of surgery, chemotherapy, and radiotherapy (RT) have shortcomings, such as large wounds, drug resistance, and easy tumor recurrence. Immunotherapy, including TCR-T-cell therapy, suppresses tumor formation and growth by enhancing the human immune system. Immunotherapy has become an increasingly reliable cancer treatment method over the past two decades, and is expected to form a new pillar industry. TCR-T-cell immunotherapy is widely used to treat cancer, viral infections, and other diseases. TCR-T cell therapy, currently in the clinical trial stage, is mainly studied for solid tumors.

In 2002, Rosenberg's team and Cassian Yee's team discovered that tumor-infiltrating lymphocytes (TIL) isolated from patients with melanoma and antigen-specific CD8+ T cells isolated from the patient's peripheral blood could be expanded *in vitro*. After the increase is infused back into the patient, it can specifically kill tumor cells and achieve a certain therapeutic effect. However, these T cells are difficult to obtain, take a long time to expand *in vitro*, and have weak anti-tumor effects after reinfusion. Therefore, researchers have explored whether known antigen-specific TCR genes could be introduced into normal peripheral blood lymphocytes (PBL). This is the origin of TCR T cells. An article published by Rosenberg's group in Science in 2006 showed that genetically modified TCR-T cells showed good application prospects in the treatment of melanoma, as 2 of the 17 patients participating in the trial developed an anti-tumor response. This study demonstrated, for the first time, the feasibility of genetically modified TCR for tumor treatment.

The development of TCR-T cell technology has undergone four key iterations, each contributing to its evolving efficacy and applicability. The first generation involved isolating tumor-infiltrating T cell subsets from a patient's tumor tissue, amplifying them *in vitro*, and reinfusing them for treatment; however, the scarcity of such T cell clones and individual variability posed challenges to industrial scalability. The second generation advanced this by obtaining antigen-specific wild-type TCR sequences through T cell cloning and transducing them into the patient's peripheral T cells, thereby enhancing the technology's industrial potential. The third generation employed affinity-optimized TCR genes to transduce either patient-specific or universal T cells, aiming to improve tumor infiltration, resistance to depletion, and anti-tumor immune suppression, thereby enhancing both the safety and efficacy of TCR-T therapy. The fourth generation builds upon this foundation by incorporating anti-depletion mechanisms, tumor chemotaxis and infiltration pathways, metabolic adaptations to the tumor microenvironment, and universal functions. These advancements not only bolster the anti-tumor capabilities of TCR-T cell immunotherapy but also enhance its safety and efficacy, with the potential to alleviate the economic burden on patients.

Global TCR-T therapy mainly targets the solid tumor market and has become an international research hotspot. Until September 2023, nearly 300 studies using TCR-T therapies are ongoing on Clinical Trials. Indications include metastatic non-small cell lung cancer, hepatocellular carcinoma, multiple myeloma, soft tissue sarcoma, head and neck cancer, melanoma, liposarcoma, and cervical cancer. As a TCR drug targeting pMHC, Kimmtrak, a bispecific T cell adapter developed by Immunocore in 2022 that can redirect T cells *in vivo*, was the first to obtain FDA approval for TCR therapy, marking a milestone breakthrough in TCR therapy targeting pMHC.

The countries with the largest number of core patent output are the USA, China, and the UK (Table 2.2.1). Cooperation between the USA and China, Germany, Switzerland, and the UK is more frequent (Figure 2.2.1). The top institutions in terms of core patent output are the USA, as represented by the Secretary Department of Health and Human Services, Guangdong Xiangxue Life Sciences Company Limited, and University of Texas (Table 2.2.2). There is no cooperative relationship among these institutions. It can be seen from the core patent-producing countries and the top institutions that China is in the forefront of the world in the R&D and industrial layout of TCR-T therapy.The number of TCR-T clinical applications in China ranks second in the world. Guangdong Xiangxue Life Sciences Company Limited, Beijing Dingcheng Taiyuan Biotechnology Company Limited, Chengdu Exab

Table 2.2.1 Countries with the greatest output of core patents on "T cell receptor engineered T cell therapy"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	USA	372	44.66	2 560	64.63	6.88
2	China	278	33.37	691	17.45	2.49
3	UK	51	6.12	262	6.61	5.14
4	Germany	37	4.44	196	4.95	5.30
5	Japan	21	2.52	40	1.01	1.90
6	Republic of Korea	16	1.92	38	0.96	2.38
7	France	14	1.68	89	2.25	6.36
8	Switzerland	13	1.56	162	4.09	12.46
9	Canada	12	1.44	38	0.96	3.17
10	Israel	10	1.20	10	0.25	1.00

Note: The selected publication date is from January 1, 2017 to December 31, 2022, the same below.

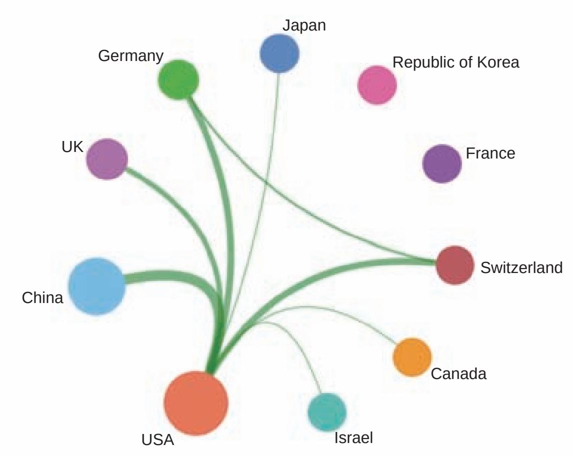

Figure 2.2.1 Collaboration network among major countries in the engineering front of "T cell receptor engineered T cell therapy"

Biotechnology Company Limited, and Guangzhou Institute of Biomedicine and Health, Chinese Academy of Sciences have become the top institutions in terms of core patent outputs. A team of Chinese scholars from Guangdong Xiangxue Life Sciences Company Limited led to the application of China's first IND for TCR-T TAEST16001. The objective response rate (ORR) for soft tissue sarcoma in Phase I clinical trials was 41.7%.

Although TCR-T cells therapy has great potential in treating tumors, how to make it widely used in clinical practice and exert its optimal efficacy is the urgent focus of TCR-T cell therapy, mainly including: how to reduce manufacturing cost and complexity, how to improve T cell persistence, how to hostile TME, and how to promote epitope spreading in order to address tumor cell escape. With other sophisticated engineering technologies such as artificial intelligence (AI), CRISPR-Cas9, high throughput screening and single cell sequencing, TCR-T cell therapy has made significant progress in antigen/target prediction, optimal affinity of TCR screening and the stability of T cell function. Therefore, the establishment of antigen target prediction model based on AI, the construction of new generation of TCR-T cells with the ability to change the TME in order to eliminate tumors, and the construction of universal TCR-T product will further deepen the application of TCR-T cells therapy in clinical practice. Figure 2.2.2 shows the roadmap of the engineering development front of "T cell receptor engineered T cell therapy".

Table 2.2.2 Institutions with the greatest output of core patents on "T cell receptor engineered T cell therapy"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	United States Department of Health and Human Services	23	2.76	162	4.09	7.04
2	Guangdong Xiangxue Life Sciences Company Limited	22	2.64	91	2.30	4.14
3	University of Texas	21	2.52	90	2.27	4.29
4	Beijing Dingcheng Taiyuan Biotechnology Company Limited	19	2.28	3	0.08	0.16
5	TCR2 Therapeutics Incorporated	18	2.16	118	2.98	6.56
6	Chengdu Exab Biotechnology Company Limited	16	1.92	65	1.64	4.06
7	University of Pennsylvania	13	1.56	97	2.45	7.46
8	University of California	12	1.44	54	1.36	4.50
9	Guangzhou Institute of Biomedicine and Health,Chinese Academy of Sciences	12	1.44	32	0.81	2.67
10	Adaptimmune Company Limited	10	1.20	86	2.17	8.60

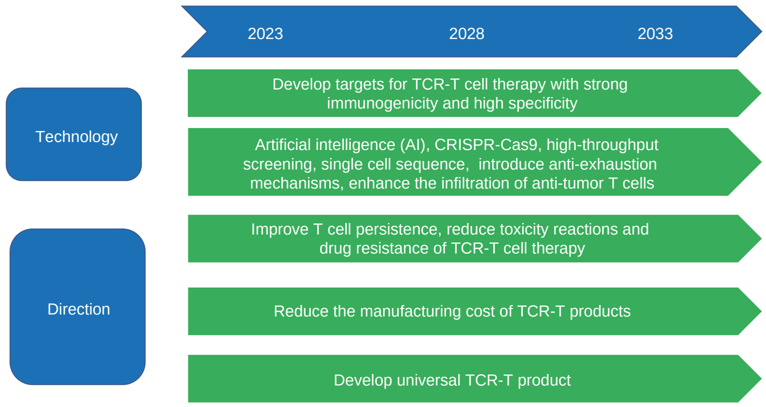

Figure 2.2.2 Roadmap of the engineering development front of "T cell receptor engineered T cell therapy"

2.2.2 Combining antibody-drug conjugates with immunotherapy for malignancies

The extent and duration of clinical benefits of using ADC alone remain suboptimal due to resistance mechanisms and patient differences. However, some ADCs have demonstrated potential for tumor immunotherapy in immunologically normal preclinical animal models, with potential mechanisms by which ADCs mediate immunogenic cell death, enhance immune infiltration, and promote PD-L1 or MHC expression to increase the sensitivity of immunotherapy. The combination of ADCs with immunotherapy is an emerging strategy, and extensive randomized clinical trials are needed to validate its superiority over standard treatments.

Combination with anti-PD-1/PD-L1 or anti-CTLA-4 antibody. Exploratory research has been conducted on HER2-targeted ADCs, such as trastuzumab emtansine (linked to DM1), trastuzumab deruxtecan (linked to Dxd), and disitamab vedotin (linked to MMAE), in combination with immune checkpoint inhibitors (ICIs), and synergistic inhibitory effects on tumor progression have been demonstrated. In an open, randomized clinical trial of ADC in combination with ICI (Study KATE2) comparing the efficacy of trastuzumab emtansine plus atezolizumab (an anti-PD-L1 antibody) and trastuzumab emtansine plus a placebo in patients with previously treated HER2+ breast cancer, the combination regimen was shown to be beneficial to the PD-L1-positive population. In models of patients with ICI-refractory melanoma and non-small cell lung cancer, enapotamab vedotin, an AXL-specific ADC, induced T cell infiltration and enhanced antigen presentation, promoting the efficacy of anti-PD-1 antibody and effectively exerting anti-tumor effects.

Combination with other immunotherapy. Polatuzumab vedotin (directed to CD79b, linked to MMAE) enhances CD20 abundance in tumors through the AKT and ERK signaling pathways, leading to a combinatorial effect with anti-CD20 antibody and CD20/CD3 bispecific antibody therapies. Belantamab mafodotin (directed to BCMA, linked to MMAF) can be combined with OX40 agonists to increase the activation of tumor-infiltrating T cells and dendritic cells for synergistic anti-tumor effects. This drug has been actively undergoing combination studies in clinical settings, such as in the DREAMM-5 project, to explore its value in combination with anti-ICOS antibodies, OX40 agonists, and anti-PD-1 antibodies.

Immune-stimulating antibody conjugates, composed of an immunostimulatory small-molecule compound linked to an antibody, an immune-stimulating antibody conjugate (ISAC), are designed to trigger the activation of tumor-associated myeloid cells and thus induce anti-tumor immune responses in a comprehensive manner. Although ISACs have the same structure as traditional ADCs, that is, the conjugate of an antibody and a small molecule, they often incorporate TLR agonists or Sting activators as small molecules, which differs from the common use of cytotoxic drugs in traditional ADCs. Moreover, the antibodies in ISACs can be targeted to tumor-associated myeloid cell antigens in addition to tumor-specific antigens, whereas those in traditional ADCs are mostly targeted only to the latter.

By utilizing antibodies, ISACs can mediate the targeted delivery of small-molecule immune agonists to the tumor microenvironment and release the payload locally, providing a solution to the immunotoxicity of small-molecule agonists in systemic administration. In terms of the mechanism of action, ISACs can activate tumor-associated myeloid cells through antibody-mediated endocytosis and increase their antigen-presenting function to further activate T cells, ultimately killing tumor cells by driving both innate immunity and adaptive immunity, and inducing long-term immune memory. Moreover, ISACs can successfully convert cold tumors into hot tumors, solving the problem of the low response rate to single immune checkpoint inhibitors.

Currently, leading companies engaged in ISACs include Bolt Biotherapeutics, Silverback Therapeutics, Tallac Therapeutics, Mersana Therapeutics, Takeda, and ImmuneSensor Therapeutics. Additionally, Jacobio, Chinook Therapeutics, Novartis, Sutro Biopharma, ALX Oncology, Seven and Eight Biopharmaceuticals, and Chinese companies such as Hengrui Pharmaceuticals, BeiGene, Innovent Bio, Shanghai Institute of Materia Medica, and Shenzhen University have also made plans for this field. Among them, Bolt Biotherapeutics, Silverback Therapeutics, and Tallac Therapeutics focus on TLR agonist-based ISACs, and Mersana Therapeutics, Takeda, and ImmuneSensor Therapeutics focus on Sting agonist-based ISACs. The most popular targets of these antibodies are HER2, NECTIN4, CCR2, CD22, PD-L1, SIRPA, ASGR1, TROP-2, and

CD73. Despite the above, ISACs still need to be explored and optimized because of their low response rates and difficulties in dose escalation in clinical settings.

In addition to the small-molecule immune agonist-antibody conjugate, immune-stimulating cytokine-antibody conjugates have also been extensively investigated in preclinical and clinical settings. Commonly used cytokines include IL-2, IFN-γ, and IL-15.

Currently, the countries with a notable number of core patent output in this front are the USA, China, and Switzerland (Table 2.2.3). As shown in the cooperation network among major countries, there is a cooperative relationship between Germany and the Netherlands, and between the USA and China, Switzerland, and other countries (Figure 2.2.3). Regeneron Pharmaceuticals Inc. (US), Immunomedics Inc. (US), and Sapreme Technologies (Netherlands) have the highest number of core patent (Table 2.2.4). There are collaborations between Sapreme Technologies (Netherlands) and Charité–Universitätsmedizin Berlin (Germany), and between The University of Texas System and Immunomedics Inc. (US) (Figure 2.2.4).

At present, the global pipelines of ADCs under development focus on the five major diseases: non-small cell lung cancer, gastric cancer, ovarian cancer, colorectal cancer, and breast cancer. The pipelines in China are mainly distributed in five major tumors: non-small cell lung cancer, gastric cancer, gastroesophageal junction cancer, breast cancer, and urothelial cancer. The most popular target of the underdeveloped ADC pipelines is HER2. Based on the development and application of the project of “combining antibody-drug conjugates with immunotherapy for malignancies”, in terms of combination therapy, it is necessary to screen out optimal combinations of ADCs with tumor immunotherapy, gradually determine the combination strategy and mechanism that can synergistically combat malignant tumors, and improve the clinical response rate and efficacy of ADCs and tumor immunotherapy. From the perspective of ISAC development, it is necessary to explore the combination of antibody targets and immunostimulatory payload targets, and optimize or upgrade the types of antibodies and linkers, conjugation strategies, payload activity, etc., to maximize the therapeutic window of ADC products and achieve a balance between pharmacological activity and safety. Extensive efforts are underway in academia and industry to establish novel ADCs or combination therapies that modulate the tumor microenvironment, gradually understand their pharmacology and related predictive biomarker combinations, and conduct preclinical evaluation in well-characterized patient-derived xenograft models to select the most promising ADC-based combinations or ISACs, providing new clinical options for precision treatment of malignancies (Figure 2.2.5).

Table 2.2.3 Countries with the greatest output of core patents on “combining antibody-drug conjugates with immunotherapy for malignancies”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citation per patent
1	USA	194	58.08	1 235	68.04	6.37
2	China	61	18.26	240	13.22	3.93
3	Switzerland	19	5.69	124	6.83	6.53
4	Germany	18	5.39	85	4.68	4.72
5	Republic of Korea	13	3.89	58	3.20	4.46
6	Netherlands	12	3.59	80	4.41	6.67
7	UK	12	3.59	67	3.69	5.58
8	France	12	3.59	36	1.98	3.00
9	India	7	2.10	52	2.87	7.43
10	Canada	5	1.50	3	0.17	0.60

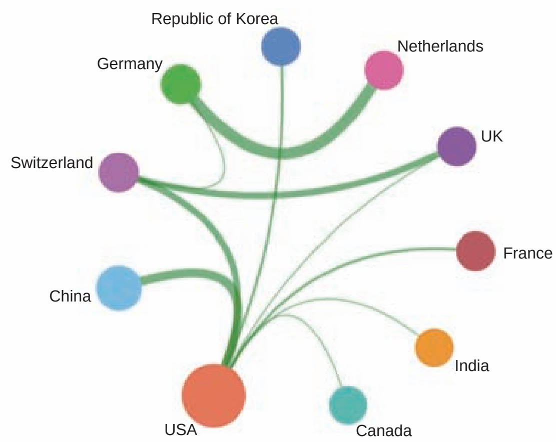

Figure 2.2.3 Collaboration network among major countries in the engineering front of “combining antibody-drug conjugates with immunotherapy for malignancies”

Table 2.2.4 Institutions with the greatest output of core patents on “combining antibody-drug conjugates with immunotherapy for malignancies”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Regeneron Pharmaceuticals Incorporated	14	4.19	126	6.94	9.00
2	Immunomedics Incorporated	11	3.29	99	5.45	9.00
3	Sapreme Technologies	11	3.29	32	1.76	2.91
4	Charité–Universitätsmedizin Berlin	9	2.69	31	1.71	3.44
5	Seagen Incorporated	9	2.69	29	1.60	3.22
6	Novartis AG	8	2.40	62	3.42	7.75
7	The University of Texas System	7	2.10	25	1.38	3.57
8	OSE Immunotherapeutics	7	2.10	22	1.21	3.14
9	Chia Tai Tianqing Pharmaceutical Group Co., Ltd.	7	2.10	16	0.88	2.29
10	AstraZeneca	6	1.80	38	2.09	6.33

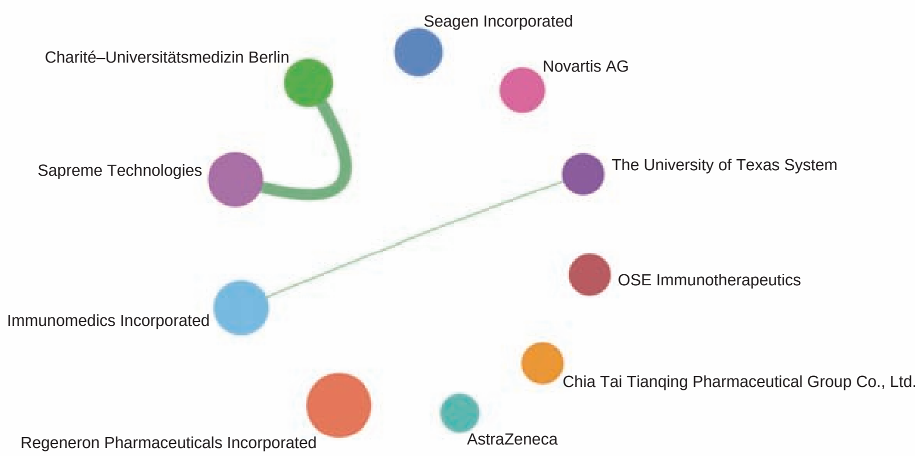

Figure 2.2.4 Collaboration network among institutions in the engineering development front of “combining antibody-drug conjugates with immunotherapy for malignancies”

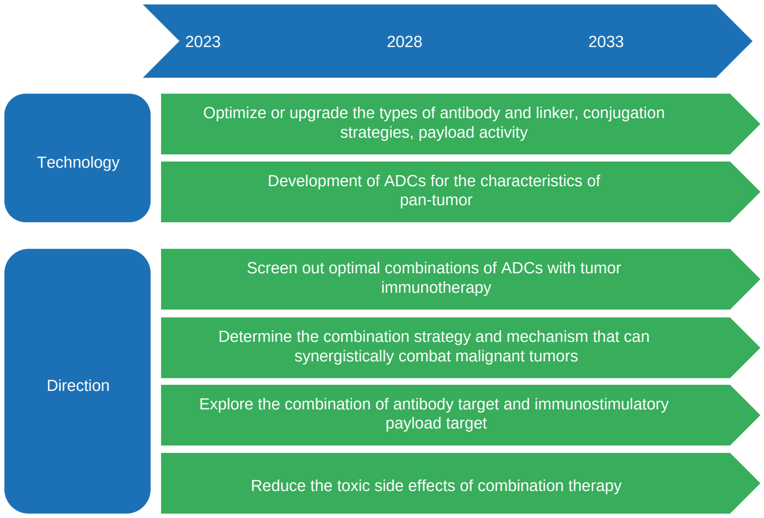

Figure 2.2.5 Roadmap of the engineering development front of "combining antibody-drug conjugates with immunotherapy for malignancies"

2.2.3 Single-cell spatial transcriptomics technology

Organ systems are composed of various cell subpopulations, and the spatial arrangement of these cell subpopulations is closely related to their functions within established tissues. Single-cell RNA sequencing (scRNA-seq) characterizes the transcriptomes of individual cells and can reveal cell subpopulations in specific organs. However, in the cell dissociation step of scRNA-seq protocols, the spatial positioning information of individuals in the native tissue is usually destroyed. By recording and reconstructing the spatial information of cells in complex tissues, single-cell spatial transcriptomics can locate single cells with transcriptional features in their native tissue environment. Integrating scRNA-seq and spatial transcriptomic data may increase our understanding of the roles of specific cell subpopulations and their interactions in development, homeostasis, and disease.

Single-cell spatial transcriptomics integrates data from single-cell transcriptome sequencing and spatial information records. Data analysis consists of two steps. First, the scRNA-seq data are used for dimensionality reduction and clustering, and subsequent deconvolution of cell type profiles within tissues and organs. Second, spatial information records are employed to map each scRNA-seq-annotated cell type to a specific niche or region of a tissue. Such analyses can provide a spatial context for the reliable evaluation of putative ligand-receptor interactions to predict intercellular signaling. Therefore, it is possible to extend insights from single-cell transcriptome-based cell typing to cell signaling research that drives phenotype changes at the protein interaction level.

Currently, spatial transcriptomic techniques are largely focused on measuring mRNA transcripts through next-generation sequencing (spatial barcoding) or fluorescent markers (HPRI). In addition to improving deconvolution and mapping algorithms, a focus that warrants attention is the development of novel deep learning models to help distinguish which features of spatial transcriptomes are the most biologically relevant. Furthermore, defining 3D spatial transcriptomes and real-time cell tracking offer additional frontiers for future technological development. These new directions will use 3D single-molecule fluorescence in situ hybridization data for computational reconstruction or inference of the location of scRNA-seq cells.

An even deeper understanding of tissue function can be achieved by extending the resolution of the spatiotemporal transcriptome by spatially resolving all biomolecules integral to the central dogma of molecular biology. For example, DBiT-seq can spatially resolve protein and mRNA transcripts within the same tissue. In situ 3D imaging of the genome, subcellular resolution of RNA, or simultaneous imaging of the nucleoli and RNA can all be performed at the single-cell level. They hold great promise in advancing our understanding of how the machinery of the central dogma functions in the 3D context of a cell to reveal the inner workings of developmental trajectories and disease.

In the future, the application of single-cell spatial transcriptomics technology in the clinical analysis of patient single cells or patient-derived *in vitro* models will help explore the molecular mechanisms of diseases and define the spatial location of rare cell types and cell subpopulations during disease progression. Furthermore, single-cell spatial transcriptomic technologies will contribute to the discovery of new therapeutic targets. The efficacy of the newly discovered drugs will then be tested in patient-derived *in vitro* models and monitored using single-cell technologies to define the cell-type-specific responses of the patient to treatment, which can then be used to specify the best therapeutic strategy for the individual patient.

The countries with the largest number of core patent output are the USA, China, and Germany (Table 2.2.5). As shown in the cooperation network among major countries, a strong cooperative relationship is most notable between the USA and the UK (Figure 2.2.6). The top institutions in terms of core patent output are the Broad Institute Incorporation, Massachusetts Institute of Technology, and University of California (Table 2.2.6). There are cooperative relationships between the Broad Institute Incorporation, MIT, Harvard University, and the University of California (Figure 2.2.7).

As more spatial transcriptomic analyses are performed, it will be increasingly challenging to disentangle definitive, disease-relevant cell types and their gene modules. With increasingly detailed annotation and mapping of cell types, tools such as Seurat Integration, Harmony, and LIGER may evolve to integrate data across different experimental assays to determine whether specific cell types are consistently observed in each tissue. Integrative single-cell spatial transcriptomic technology is rapidly developing. Depending on the biological questions being asked, the experimental methodology can be designed to integrate any spatial transcriptomic approach with other scRNA-seq technologies. In addition to developing enhanced methods, careful selection of algorithms for integrating such data is of paramount importance because methods that spatially resolve tissue organization at the resolution of conventional scRNA-seq technologies or at the depth of whole-transcriptome coverage do not yet exist. Integrating the analysis of multiple approaches is beginning to shed light on the spatial maps of specific cell subpopulations in development and disease and to reveal the mechanisms whereby such cell populations collaboratively shape tissue phenotypes (Figure 2.2.8).

Table 2.2.5 Countries with the greatest output of core patents on “single-cell spatial transcriptomics technology”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citation per patent
1	USA	83	51.23	743	78.87	8.95
2	China	61	37.65	190	20.17	3.11
3	Germany	4	2.47	1	0.11	0.25
4	UK	2	1.23	4	0.42	2.00
5	Netherlands	2	1.23	3	0.32	1.50
6	Japan	2	1.23	1	0.11	0.50
7	Belgium	2	1.23	0	0.00	0.00
8	Switzerland	1	0.62	0	0.00	0.00
9	Finland	1	0.62	0	0.00	0.00
10	France	1	0.62	0	0.00	0.00

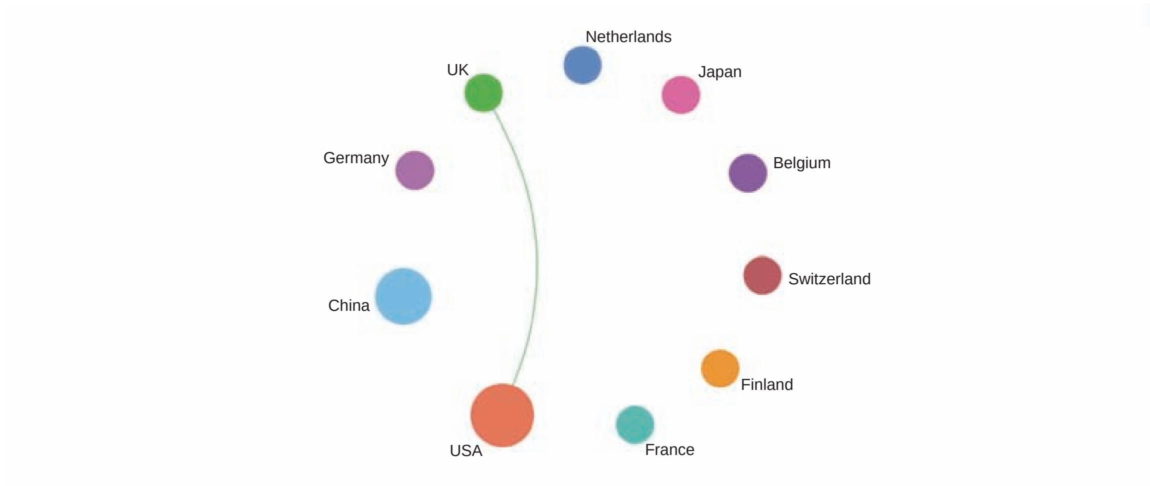

Figure 2.2.6 Collaboration network among major countries in the engineering development front of "single-cell spatial transcriptomics technology"

Table 2.2.6 Institutions with the greatest output of core patents on "single-cell spatial transcriptomics technology"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	The Broad Institute Incorporation	17	10.49	173	18.37	10.18
2	Massachusetts Institute of Technology	15	9.26	203	21.55	13.53
3	University of California	7	4.32	43	4.56	6.14
4	Stanford University	7	4.32	22	2.34	3.14
5	Bio-Rad Laboratories Incorporated	6	3.70	50	5.31	8.33
6	Harvard University	5	3.09	107	11.36	21.40
7	10x Genomics Incorporated	5	3.09	86	9.13	17.20
8	University of Washington	4	2.47	19	2.02	4.75
9	Southeast University	4	2.47	12	1.27	3.00
10	Sigma-Aldrich Company Limited	4	2.47	11	1.17	2.75

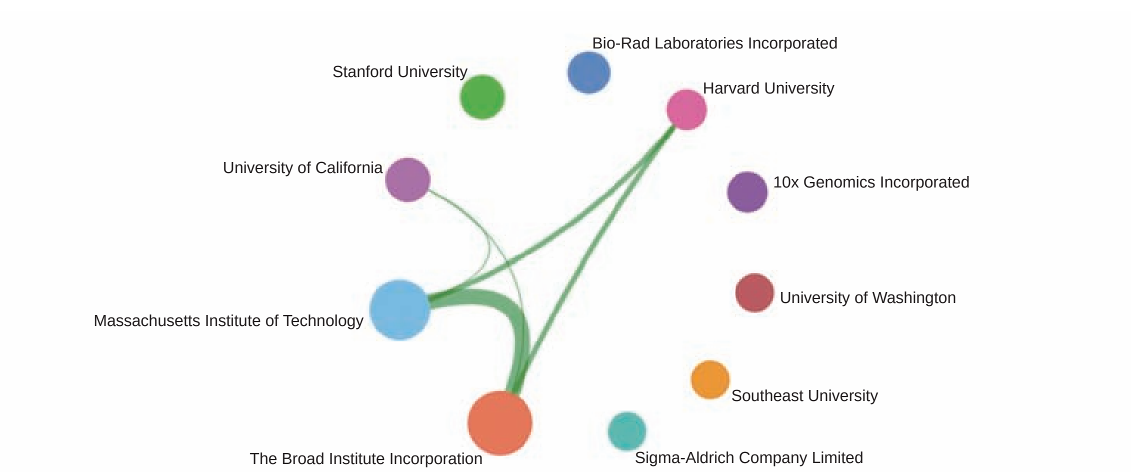

Figure 2.2.7 Collaboration network among major institutions in the engineering development front of "single-cell spatial transcriptomics technology"

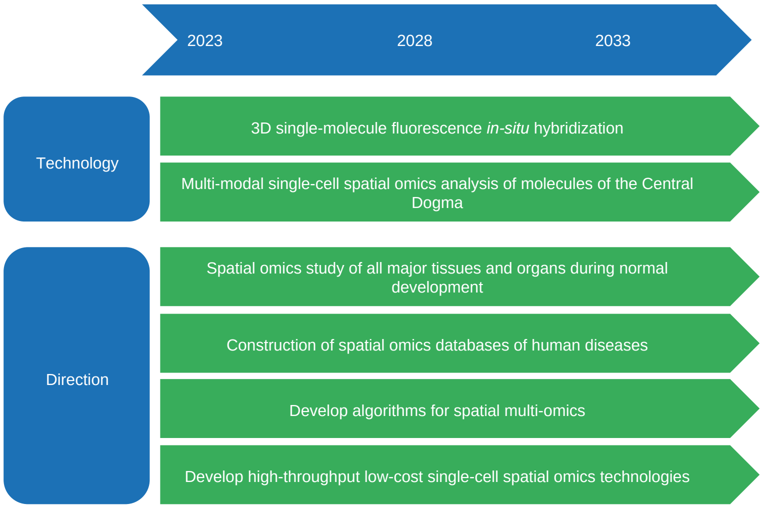

Figure 2.2.8 Roadmap of the engineering development front of "single-cell spatial transcriptomics technology"

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IX. Engineering Management

1. Engineering research fronts

1.1 Trends in Top 10 engineering research fronts

In the field of engineering management, the global Top 10 engineering research frontiers this year are "research on human–machine symbiotic intelligent manufacturing under Industrial 5.0 environment", "research on unmanned aerial vehicle dispatching and path optimization in logistics", "research on symbiotic logic and governance of major engineering innovation ecosystems", "research on enhancing and ensuring the resilience of transportation networks", "research on evolution and governance of public safety incidents driven by big data", "research on product quality and reliability technology in a big data environment", "research on interactive mechanism and coordinated development rules of energy economy and environmental systems", "research on intrinsic mechanism of digital empowerment value creation in manufacturing enterprises", "research on precision medical process optimization", and "research on pricing and revenue sharing mechanism of digital elements". Citations to seminal articles pertinent to these topics can be found in Tables 1.1.1 and 1.1.2. Among these domains, particular attention is accorded to "research on human–machine symbiotic intelligent manufacturing under Industrial 5.0 environment", "research on unmanned aerial vehicle dispatching and path optimization in logistics" and "research on symbiotic logic and governance of major engineering innovation ecosystems". Succeeding sections will offer a robust analysis of their extant developmental trajectories and prospective orientations.

(1) Research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment

Industrial 5.0 heralds a novel phase in the evolution of manufacturing, building upon the foundations laid by the 4.0 stage, with an

Table 1.1.1 Top 10 engineering research fronts in engineering management

No.	Engineering research front	Core Papers	Citation	Citations per paper	Mean year
1	Research on human–machine symbiotic intelligent manufacturing under Industrial 5.0 environment	29	2 270	78.28	2021.2
2	Research on unmanned aerial vehicle dispatching and path optimization in logistics	45	4 913	109.18	2018.9
3	Research on symbiotic logic and governance of major engineering innovation ecosystems	45	986	21.91	2020.1
4	Research on enhancing and ensuring the resilience of transportation networks	4	227	56.75	2020.0
5	Research on evolution and governance of public safety incidents driven by big data	13	870	66.92	2018.2
6	Research on product quality and reliability technology in a big data environment	17	99	5.82	2019.8
7	Research on interactive mechanism and coordinated development rules of energy economy and environmental systems	11	144	13.09	2021.2
8	Research on intrinsic mechanism of digital empowerment value creation in manufacturing enterprises	25	628	25.12	2019.2
9	Research on precision medical process optimization	31	383	12.35	2019.8
10	Research on pricing and revenue sharing mechanism of digital elements	15	230	15.33	2020.1

Table 1.1.2 Annual number of core papers published for the Top 10 engineering research fronts in engineering management

No.	Engineering research front	2017	2018	2019	2020	2021	2022
1	Research on human–machine symbiotic intelligent manufacturing under Industrial 5.0 environment	0	1	3	3	4	18
2	Research on unmanned aerial vehicle dispatching and path optimization in logistics	5	11	15	11	3	0
3	Research on symbiotic logic and governance of major engineering innovation ecosystems	3	4	6	7	10	13
4	Research on enhancing and ensuring the resilience of transportation networks	0	1	0	1	2	0
5	Research on evolution and governance of public safety incidents driven by big data	4	4	3	2	0	0
6	Research on product quality and reliability technology in a big data environment	3	1	5	1	1	6
7	Research on interactive mechanism and coordinated development rules of energy economy and environmental systems	0	1	0	2	1	7
8	Research on intrinsic mechanism of digital empowerment value creation in manufacturing enterprises	6	4	5	3	3	4
9	Research on precision medical process optimization	3	4	4	11	3	6
10	Research on pricing and revenue sharing mechanism of digital elements	1	3	2	2	1	6

emphasis on human-centered approaches designed to realize more sustainable and resilient production processes. At the heart of Industrial 5.0 lies the concept of Human–Machine Symbiosis Intelligent Manufacturing, an integrated system comprising human–human, human–machine, and machine–machine interactions. These interactions are orchestrated to operate in harmony across both physical and virtual domains, leveraging the collaboration and coevolution of human beings and intelligent machines. The system combines the precision and strength of robotics with the advanced cognitive abilities and flexibility of humans, allowing adaptation to perpetually evolving circumstances and demands.

Contemporary advancements in front-end technologies, such as intelligent sensing, brain–machine interfaces, and the Internet of Things, along with foundational technologies, including cloud computing, big data, large models, and artificial intelligence, have led to machines progressively manifesting intelligent and autonomous characteristics. The traditional unifunctional nature of machine operations has metamorphosed into multifaceted processes encompassing perception, comprehension, planning, decision-making, and execution. Machines have advanced from being controlled entities to autonomous intelligent agents, and the human–machine relationship has matured from a “supportive, subordinate” level to stages of “collaborative, equal”, and “integrative, symbiotic” interaction.

Unlike the traditional realm of human–machine interaction, which predominantly concentrates on machine adaptation to human needs for effective collaboration, human–machine symbiosis intelligent manufacturing extends this paradigm. It emphasizes the exploration of three technological strata: human–machine mutual perception–cognition–trust, human–machine collaborative organization–planning–decision–making, and human–machine collaborative interaction–control–evolution. The overarching goal is the scalable, flexible, and automated production of personalized and highly complex products.

Looking forward, the rapid advancement of human–machine symbiosis intelligent manufacturing will undoubtedly catalyze the emergence of innovative business models and value chains within the manufacturing industry.

(2) Research on unmanned aerial vehicle dispatching and path optimization in logistics

In densely populated urban regions, there is a serious deficiency in land resources available for road construction, which leads to increasingly acute problems of traffic congestion and pollution. Concurrent with the rapid advancement of logistics unmanned aerial vehicles (UAVs) and the exploration of three-dimensional space, the transition from ground logistics transport to aerial transport has emerged as a new trend in the development of urban logistics. Many domestic and international logistics companies have recognized the efficiency advantages of drone delivery and have commenced comprehensive verification.

International logistics titan Amazon has deployed Prime Air drones, with an emphasis on the development of last-mile delivery from warehouses to suburban customers. Concurrently, DHL is dedicated to establishing drone stations to facilitate the delivery of goods in remote areas. In 2019, UPS partnered with CVS Pharmacy to transport home medical supplies in suburban and rural areas, while Wing focused on commercial food delivery drone research. China's Rapid Ant Technology Co., Ltd. began with suburban postal delivery and then gradually transitioned to urban delivery and medical reagent transport. Meituan, capitalizing on its resources in food delivery, has aggressively pursued urban drone instant delivery. JD.com has centered its efforts on the "last mile" in rural areas while simultaneously expanding a three-tier drone transport network encompassing trunk, branch, and terminal levels.

Compared to traditional ground logistics transportation, drone logistics transport offers a significant increase in speed but is not without its drawbacks. These include a low single-drone payload, short flight range, and the frequent necessity for battery replacement. Therefore, unique research problems have arisen in drone logistics following its emergence, which distinguishes it from ground logistics scheduling. These include challenges related to drone logistics path planning, coordination of transport path planning between drones and ground vehicles, and scheduling optimization.

(3) Research on the symbiotic logic and governance of major engineering innovation ecosystems

Mega-projects refer to large-scale public initiatives characterized by substantial investment, extended implementation cycles, technical complexity, and far-reaching impacts on society, economy, and the ecological environment. Within the context of innovation-driven high-quality development, mega-projects serve as pivotal platforms for fostering peaks of innovation, and the construction of a symbiotic and prosperous mega-project innovation ecosystem represents one of the research frontiers in the field of project management. A mega-project innovation ecosystem is a tightly interconnected and co-evolving network formed by various innovation actors—including project owners, designers, constructors, consulting agencies, academic institutions, research organizations, and governmental departments—in the pursuit of effective systemic solutions to the technical challenges faced by mega-projects. The notion of "symbiosis" within this innovation ecosystem refers to the mutually beneficial and interdependent relationships established among different types of innovation actors as they collaborate to overcome technical challenges and seek solutions. Investigating governance strategies for the symbiotic logic among innovation actors within the mega-project innovation ecosystem can facilitate the efficient operation of the ecosystem and the synergistic development of its constituent actors, thereby providing insights for optimizing innovation management in mega-projects.

(4) Research on the enhancement and safeguarding of transportation network resilience

With the rapid expansion of transportation demands and the frequent occurrence of various disasters and unexpected events, ensuring and enhancing the transportation capacity and efficiency of the transportation network has gained significant importance. Maintaining and bolstering the resilience of the transportation network has emerged as a critical and pressing issue within the realm of engineering management. Transportation network resilience pertains to the transportation system's ability to withstand or absorb the impacts of external disturbances or attacks and subsequently return to normal operational levels.

In accordance with the concept and definition of transportation network resilience, ongoing research primarily engages in safeguarding and enhancing network resilience through the following avenues. First, it delves into measurement methods and an assessment index system for network resilience grounded in network topology structure and system performance. Second, through the monitoring of disaster factors within the road network, simulations of disaster early warnings, analyses of network redundancy, assessments of traffic capacity, and the optimization design of capacity, research investigates methods and technologies for pre-event transportation network resilience enhancement.

Third, it explores the augmentation of the network's resistance and absorptive capacity during disaster impacts. This includes identifying and managing critical infrastructure, optimizing the allocation of emergency resources within the network, making network response decisions, and implementing network emergency controls. Finally, research undertakes the optimization of restoration strategies for the network, resource allocation for restoration, and the enhancement of system function recovery. This addresses post-event network recovery decision-making and the optimization of resource allocation, thereby ensuring the dependable and swift enhancement of the resilience of the transportation network system.

Ongoing research still requires innovative work in data mining and mechanism analysis related to characteristics of disaster intensity distribution, the evolution and mutation rules of travel demand, the coupling of multimodal transportation systems, and the collaborative optimization of complex systems, among others. In the foreseeable future, this research frontier is poised to generate novel growth opportunities in the domains of integrated transportation, collaborative efforts between vehicles and roadways, the integration of multiple networks, big data technology, intelligent control, and more. These developments bring forth challenges and prospects for research in transportation infrastructure operation and management.

(5) Research on the evolutionary law and governance of social public safety incidents driven by big data

Amidst the swift progression of the social economy and the ongoing intensification of urbanization, diverse incidents impacting public safety have found a fertile ground to develop. These incidents encompass natural calamities, industrial mishaps, traffic collisions, criminal activities, contagious ailments, and other unforeseen emergencies. Gradually, they are evolving into tangible menaces that undermine urban security, hinder economic advancement, and disrupt societal equilibrium. Concurrently, as technology advances, significant opportunities have arisen through the integration of big data technologies like 5G, deep learning, and cloud services. This integration holds immense potential for studying and managing social public safety incidents.

Big data technology, encompassing the comprehensive collection, analysis, and application of voluminous data from multiple sources, has witnessed extensive implementation across domains such as finance, manufacturing, and public services. In recent years, its utilization has penetrated deeply into the realm of social public safety incident research and management. Research endeavors span all phases of big data utilization, including collection, analysis, and application. Key areas of investigation encompass: the acquisition, aggregation, and retention of significant data related to social public safety incidents, driven by innovative technologies like 5G and blockchain; the application of data mining, deep learning, artificial intelligence, and analogous algorithms to discern the genesis and progression of these incidents; leveraging the advancements in Internet of Things and data infrastructure to develop big data-driven technologies for managing social public safety incidents, while simultaneously conceptualizing suitable administrative frameworks.

As the evolution of smart cities continues, the horizon for the application of big data technology within the realm of social public safety incident research and management expands significantly. Future research trajectories are expected to intertwine closely with the multi-tier structure of smart cities. This encompasses the assimilation of big data perception, analysis, and application, grounded in the city information model (CIM). Additionally, research efforts will be informed by iterative optimizations based on insights drawn from established smart cities, thereby setting a trajectory for future advancements.

(6) Research on product quality and reliability technology in the big data environment

With the progression of science and technology, especially in the realm of information technology, industrial big data has undergone explosive growth. This growth provides the requisite data support environment and conditions for the analysis, control, and enhancement of product quality and reliability. Industrial big data not only encapsulates the entire life cycle processes of product design, manufacturing, maintenance, scrapping, recycling, and remanufacturing but also encompasses information related to the product usage environment and user perception. It significantly facilitates the comprehensive application of artificial intelligence in product manufacturing, usage, and maintenance. The research on product quality and reliability within the big data environment can be categorized into two primary aspects.

First, the foundation of product quality analysis theory and methods relies on the digitization of the entire “design–manufacture–sale–use” process. Key research directions in this area include the horizontal and vertical integration of quality and reliability industrial big data across the product life cycle and supply chain. Data fusion and intelligent quality management within manufacturing systems. Precise tracing of product quality throughout the entire lifecycle, leveraging IoT, blockchain, and identification resolution technologies. Digital quality control is propelled by multimodal fusion and digital twin technology. Intelligent maintenance services are fortified by intelligent sensing, knowledge graphs, and natural language processing. Networked supply chain quality control incorporating blockchain technology. Personalized custom product intelligent design and quality control, employing industrial big model technologies. Complex product reliability analysis theory and methods concentrate on intricate equipment reliability modeling, analysis, assessment, and optimization. These transcend the constraints of the independent unit statistical assumption, taking into account unit correlation ubiquity, data and model-driven complex equipment remaining life prediction, and maintenance analysis theory and methods.

Second, the emphasis is placed on human–machine integration as the cornerstone of product quality and reliability analysis theory and methods. Key research directions here include human–machine (intelligent machines) collaborative product quality control and management techniques. Reliability modeling, analysis, and optimization theory and methodologies for human-integrated intelligent product systems.

(7) Research on the interactive impact mechanism and coordinated development laws of energy economy and environmental systems

Presently, global economic, social, and energy–environment systems are undergoing profound transformations. The interplay between climate governance, energy security, environmental enhancement, and socioeconomic developmental goals is deepening. Notably, the prominence of cascading, compounded, and uncertain factors affecting decision outcomes and risk propagation is growing. Consequently, there is an escalating emphasis on comprehensively considering the interconnectedness of system components within simulation models of the energy-environment-economy complex system. This approach is pivotal in ensuring the stability of the environmental-economic system and prudently advancing dual carbon objectives. The ongoing principal research directions encompass the following aspects. ① Complex system modeling and evolutionary trend analysis with dual carbon orientation: this entails coupling diverse energy models with meteorological and land-use models to construct intricate comprehensive assessment models. A notable example is IIASA's MESSAGEix-GLOBIOM model. These models facilitate a spectrum of scenario simulations, and they play a fundamental role in guiding path decisions. ② Research on multielement coordinated development paths driven by pollution and carbon reduction objectives: rooted in the modeling of the energy-environment-economy complex system, this research integrates multielement constraint functions. The goal is to optimize paths that coordinate pollution reduction and carbon reduction in accordance with principles that maximize coordinated benefits and public welfare while minimizing policy costs. ③ Measurement and modeling of adaptive behavior: within the intricate web of decisions concerning pollution reduction and carbon reduction, entities exhibit adaptability. They formulate targeted adjustment strategies in response to alterations in policy and market environments, thereby influencing system evolution. Quantifying adaptive behavior facilitates a cross-simulation of behavior, climate, and economy. The process of selecting effective adaptive approaches stands as a current critical frontier. Furthermore, the decision-making associated with pollution and carbon reduction contends with uncertainties emanating from various sources. These encompass outcomes from predictive models, occurrences of extreme climate events, and leaps in technological costs. In the future, a key developmental trajectory is navigating robust decision-making within the energy-environment-economy system amidst profound uncertainty. This necessitates integrating diverse stakeholder perspectives into decision-making and exploring the tripartite equilibrium between risk, cost, and resilience across diverse plausible scenarios.

(8) Study on the intrinsic mechanism of value creation through digital empowerment in manufacturing enterprises

Value creation through digital empowerment in manufacturing enterprises entails leveraging technologies such as artificial intelligence, digital twins, and edge computing. This process follows a systematic sequence of data perception, intelligent cognition, dynamic decision-making, and precise execution. It necessitates establishing effective perception mechanisms to sense objects and gather data and subsequently employing system analysis models to translate voluminous data into valuable insights and knowledge for comprehending objects. The application of dynamic decision-making comes into play across diverse scenarios, harmonizing a range of resources, including data, materials, human resources, and finances. This fosters the streamlined and efficient execution of manufacturing enterprise activities. Drawing from the outcomes of dynamic decisions, the meticulous execution of action plans materializes, accompanied by real-time feedback and proficient control. This engenders a cycle of reducing costs, enhancing quality, boosting efficiency, and ultimately yielding efficient value creation. To elaborate further, manufacturing enterprises heighten their operational capacities by seamlessly integrating digital technology into strategic decision-making, research and development, materials procurement, production, marketing services, and organizational management. This expansion enhances their competence in describing, diagnosing, predicting, deciding, and overseeing operational conditions. This holistic integration markedly elevates the impact, efficiency, and benefits of value creation. Moreover, digital technology serves as a catalyst for the integration of industrial chains, value chains, innovation chains, and capital chains. This augments collaboration and cooperation between enterprises, nurturing transformations across industrial elements, organizational structures, innovation systems, and business models. In turn, this impels the evolution and advancement of the manufacturing industry. Finally, while embarking on the journey of value creation through digital empowerment in manufacturing enterprises, critical concerns such as privacy breaches, data rights validation, algorithmic biases, and technology misuse must be addressed. These efforts are vital for ensuring enterprise security and industrial stability. This imperative calls for continuous enhancements at both the policy and technical levels.

(9) Research on precision medical process optimization

Precision medicine epitomizes a personalized medical paradigm grounded in data-driven methodologies. It furnishes patients with tailored preventive and treatment strategies based on their genetic, environmental, and lifestyle particulars. The chief pursuits of precision medicine encompass the personalized calibration of treatment regimens, early ailment detection, drug innovation, and biomarker identification, among others.

At its core, precision medicine draws strength from extensive, multidimensional, and high-quality biomedical data, including genomic and vital sign information. These data are gleaned through sequencing technologies and wearable devices. This profusion of data renders possible personalized, exact, and cost-effective disease prevention, diagnosis, and treatment. The COVID-19 pandemic underscored this when large-scale sequencing data and population mobility insights facilitated precise disease control strategies.

Precision medicine harnesses methodologies such as mathematical modeling and optimization algorithms to formulate optimal treatment decision protocols rooted in patients' health status and treatment outcomes. These protocols can account for both immediate and delayed treatment impacts, or they can optimize diverse anticipated objectives such as treatment effects and patient quality of life. Notably, for chronic conditions such as cancer and Alzheimer's disease, the shift from traditional maximum tolerable dose approaches to precision medicine has been proposed by experts.

Furthermore, precision medicine leverages the "virtual physiological human (VPH)" to simulate a myriad of physiological processes and organ functions within the human body. It also capitalizes on extensive language models for retrieving biomedical information. The domains of cancer, Alzheimer's disease, infectious diseases, and beyond hold vast potential for precision medicine applications. By delving into the mechanisms underlying disease initiation, which entails identifying disease-associated biological targets and assessing treatment outcomes via biomarkers, precision medicine stands poised to deliver more effective and safer therapeutic interventions.

By harnessing big data analysis and artificial intelligence, precision medicine enhances the timeliness and convenience of diagnostic services. Through wearable devices and smartphones, it furnishes personalized and continuous health management. The arena of precision medicine is thriving, emerging as one of the most vigorously pursued investment domains in both academia and industry. Crucially, the optimization of the precision medicine process assumes a pivotal role across numerous levels, encompassing data collection and organization, model construction, and decision analysis, and necessitates interdisciplinary collaborations between scholars in the medical, information science, and management science fields. This collaborative impetus is pivotal in further elevating the health and hygiene landscape within our nation.

(10) Research on the pricing and revenue sharing allocation mechanism of digital elements

One of the fundamental strategies for fully unlocking the value inherent in data elements rests upon the circulation of these elements. Similarly, a pivotal aspect contributing to the active circulation of data elements lies in the effective implementation of pricing mechanisms and allocation strategies for revenue sharing. At present, notable advancements have been made in the exploration of mechanisms and approaches for pricing data elements, as well as methods for distributing revenue, within diverse domains encompassing computer science, data science, management studies, and economics.

In the domain of data element pricing, the realm of computer science is primarily engaged in investigating strategies for pricing data based on its contributions to AI models, along with methodologies for pricing rooted in privacy compensation. In parallel, data science and economics have proffered techniques for pricing data grounded in principles such as equity, revenue optimization, absence of arbitrage discrepancies, and information entropy. The realm of management studies has proposed diverse data pricing methodologies, including expert assessment scoring, hierarchical analysis, and supply-demand alignment tailored to distinct contextual settings.

In the realm of revenue-sharing allocation for data elements, management studies have predominantly concentrated on the exploration of multiparty revenue distribution within Internet service platforms. Meanwhile, economics has placed significant emphasis on research aligned with the marginal contribution stemming from data.

As China accelerates the establishment of fundamental data element frameworks, coupled with the systematic progress of the data element circulation market, along with its supporting technological infrastructure, the evolution toward data productization will continue to mature. It is imperative that the examination of pricing and revenue-sharing allocation mechanisms for data elements be comprehensively and thoroughly pursued. Prospective directions for development within this sphere encompass: ① a comprehensive consideration of the novel attributes exhibited by data elements in the formation of market-based pricing frameworks, including underlying theories and methodologies; ② an interconnected analysis of the complete lifecycle of data elements, entailing the investigation of revenue-sharing allocation mechanisms and regulations embodying the principle of “market-assessed contribution, remuneration determined by contribution”, underpinned by state-of-the-art technology within the realm of data element circulation; and ③ an alignment with the structural configuration of data element property rights, necessitating research into data pricing and revenue-sharing allocation methodologies contingent on application scenarios. This includes a thorough exploration of varied pricing techniques and revenue-sharing allocation regulations pertaining to the authorized utilization of public data.

1.2 Interpretations for three engineering research fronts

1.2.1 Research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment

Human–machine engineering was first conceptualized as far back as the mid-nineteenth century, with its primary focus being the harmonization of human, machine, and environmental elements during operations, enabling the efficient and safe utilization of machinery. With the widespread adoption of computers in the 1980s, human–machine interaction primarily centered around enhancing feedback loops between machines and humans, aiming to enhance machine adaptability to human needs. Since 2008, driven by the imperative of personalized manufacturing, the idea of human–machine collaboration has gained consensus within industrial manufacturing. This collaboration envisions the sharing of resources and capabilities between humans and machines during the manufacturing process. This phase initially explored non-semantic perception and shallow intelligence. Subsequently, with the emergence of cognitive computing, large-scale models, knowledge evolution, and similar advancements, human–machine collaboration has evolved toward symbiosis, initiative, and integration within the context of the Industrial 5.0 paradigm.

Contemporary research into human–machine symbiotic intelligent manufacturing predominantly centers on three key aspects. ① The foundation of human–machine symbiosis lies in mutual perception, cognition, and trust. This is realized through technologies such as the Internet of Things and digital twins, offering a comprehensive understanding of machine task execution.

Additionally, through knowledge acquisition and ergonomics analysis, machines are enabled to perceive and interpret human intentions. ② The core of human–machine symbiosis is the collaborative organization, planning, and decision-making processes between humans and machines. This entails self-organization within the broader system, the planning of human–machine movements and system resource allocation, and the application of intelligent decision-making during production. ③ At the heart of human–machine symbiosis is collaborative interaction, control, and evolution. This involves rich interactions between humans and machines, introducing human cognitive models into machine intelligence through methodologies such as deep learning. This enhances machine skill strategy optimization, imbuing machines with higher-level intelligence and capability for more intricate collaborative tasks.

Although human–machine symbiotic intelligent manufacturing is progressing from interactive collaboration to deeper bidirectional cognition and higher-level intelligent integration, it remains at an early stage. Numerous challenges persist, such as real-time human–machine–environment perception analysis, fostering human–machine trust and addressing machine psychological concerns, allocating tasks to multiple individuals and machines in abnormal situations, creating plug-and-play scalable human–machine AI agents, and more. Despite these challenges, human–machine symbiotic intelligent manufacturing is in the ascendant phase, steadily advancing toward comprehensive, diverse, and systematic integration as it gains momentum in various industrial applications.

In the front of "research on human–machine symbiotic intelligent manufacturing under the Industrial 5.0 environment", the foremost countries based on core paper count are the USA, China, and Sweden (Table 1.2.1). Leading institutions in terms of core paper output include KTH Royal Institute of Technology, Hong Kong Polytechnic University, and University of Patras (Table 1.2.2). Analyzing the main collaborative network among countries (Figure 1.2.1), the USA emerges as a prominent collaborator with various nations. Examining major institutional collaborations (Figure 1.2.2), it is evident that the KTH Royal Institute of Technology, Hong Kong Polytechnic University, University of Patras, and Beijing Institute of Technology have established close collaborative ties. As indicated in the Table 1.2.3, the USA ranks first, followed by China in terms of citing paper counts. Notably, the key institutions for citing paper counts include KTH Royal Institute of Technology, George Washington University, and University of Oulu (Table 1.2.4).

The Figure 1.2.3 illustrates the developmental trajectory of the front of "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment". Fueled by the imperative for personalized, intricate product scaling, flexibility, and automation in production, pivotal technologies such as human–machine mutual perception–cognition–trust, human–machine collaborative organization–planning–decision, and human–machine collaborative interaction–control–evolution are being innovated. This evolution marks a shift from "individual intelligence integration" toward "collective intelligence integration" and "intelligent coevolution", culminating in a novel manufacturing paradigm characterized by the mutual and symbiotic coexistence of humans and machines.

Table 1.2.1 Countries with the greatest output of core papers on "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per aper	Mean year
1	USA	13	44.83	633	48.69	2021.5
2	China	7	24.14	569	81.29	2021.7
3	Sweden	5	17.24	446	89.20	2021.4
4	Greece	5	17.24	183	36.60	2022.0
5	India	4	13.79	493	123.25	2020.8
6	Republic of Korea	3	10.34	402	134.00	2021.7
7	Australia	3	10.34	392	130.67	2020.7
8	Germany	3	10.34	297	99.00	2021.7
9	Italy	3	10.34	283	94.33	2020.3
10	Turkey	3	10.34	242	80.67	2020.7

Table 1.2.2 Institutions with the greatest output of core papers on “research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	KTH Royal Institute of Technology	4	13.79	366	91.50	2021.8
2	Hong Kong Polytechnic University	3	10.34	177	59.00	2022.0
3	University of Patras	3	10.34	112	37.33	2022.0
4	University of Auckland	2	6.90	285	142.50	2021.5
5	University of Johannesburg	2	6.90	278	139.00	2022.0
6	Beijing Institute of Technology	2	6.90	81	40.50	2022.0
7	Zhejiang University	2	6.90	81	40.50	2022.0
8	George Washington University	2	6.90	73	36.50	2022.0
9	Berlin School of Economics and Law	2	6.90	71	35.50	2022.0
10	Deakin University	1	3.45	281	281.00	2019.0

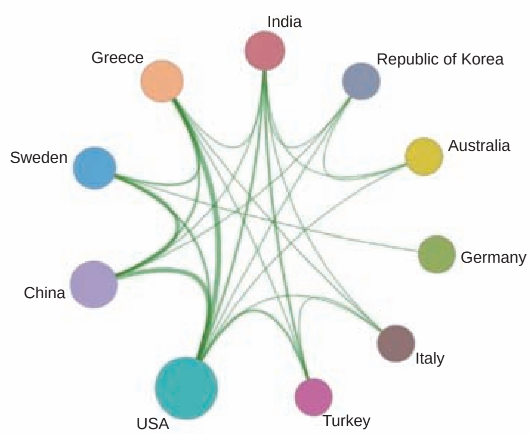

Figure 1.2.1 Collaboration network among major countries in the engineering research front of “research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment”

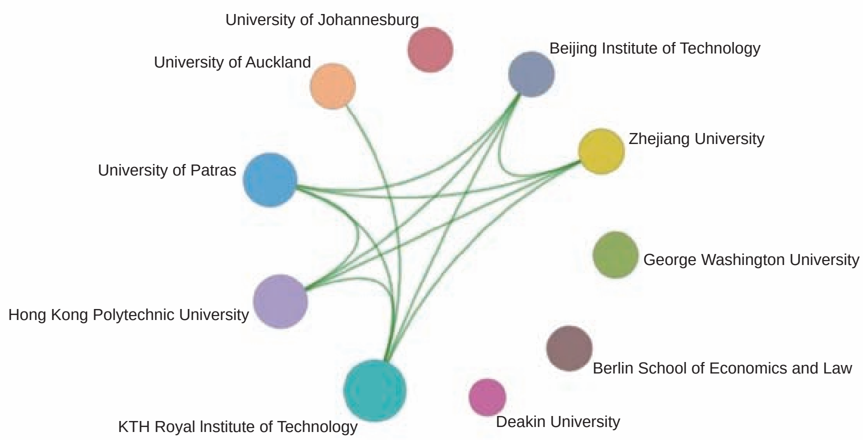

Figure 1.2.2 Collaboration network among major institutions in the engineering research front of “research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment”

Table 1.2.3 Countries with the greatest output of citing papers on "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	USA	31	17.32	2021.4
2	China	29	16.20	2021.5
3	UK	21	11.73	2021.2
4	India	21	11.73	2021.2
5	Italy	15	8.38	2020.5
6	Kingdom of Saudi Arabia	11	6.15	2021.6
7	Sweden	11	6.15	2021.5
8	Canada	11	6.15	2020.6
9	Germany	10	5.59	2021.3
10	Brazil	10	5.59	2020.9

Table 1.2.4 Institutions with the greatest output of citing papers on "research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	KTH Royal Institute of Technology	6	13.95	2021.8
2	George Washington University	5	11.63	2021.6
3	University of Oulu	4	9.30	2021.5
4	Ismaili Muslim University	4	9.30	2020.8
5	Velore Institute of Technology	4	9.30	2022.0
6	University of Johannesburg	4	9.30	2021.2
7	Hong Kong Polytechnic University	4	9.30	2022.0
8	Taif University	3	6.98	2021.7
9	Berlin School of Economics and Law	3	6.98	2022.0
10	Deakin University	3	6.98	2021.3

1.2.2 Research on unmanned aerial vehicle dispatching and path optimization in logistics

In recent years, researchers both domestically and internationally have been exploring various logistical elements related to unmanned aerial vehicles (UAVs), ground take-off and landing facilities, and logistics warehouses. These investigations encompass a range of topics, including path planning, scheduling optimization, trajectory optimization, and operational management.

(1) UAV logistics path planning in urban scenarios

Research in this area encompasses topics such as the traveling salesman problem with drones (TSP-D), the vehicle routing problem

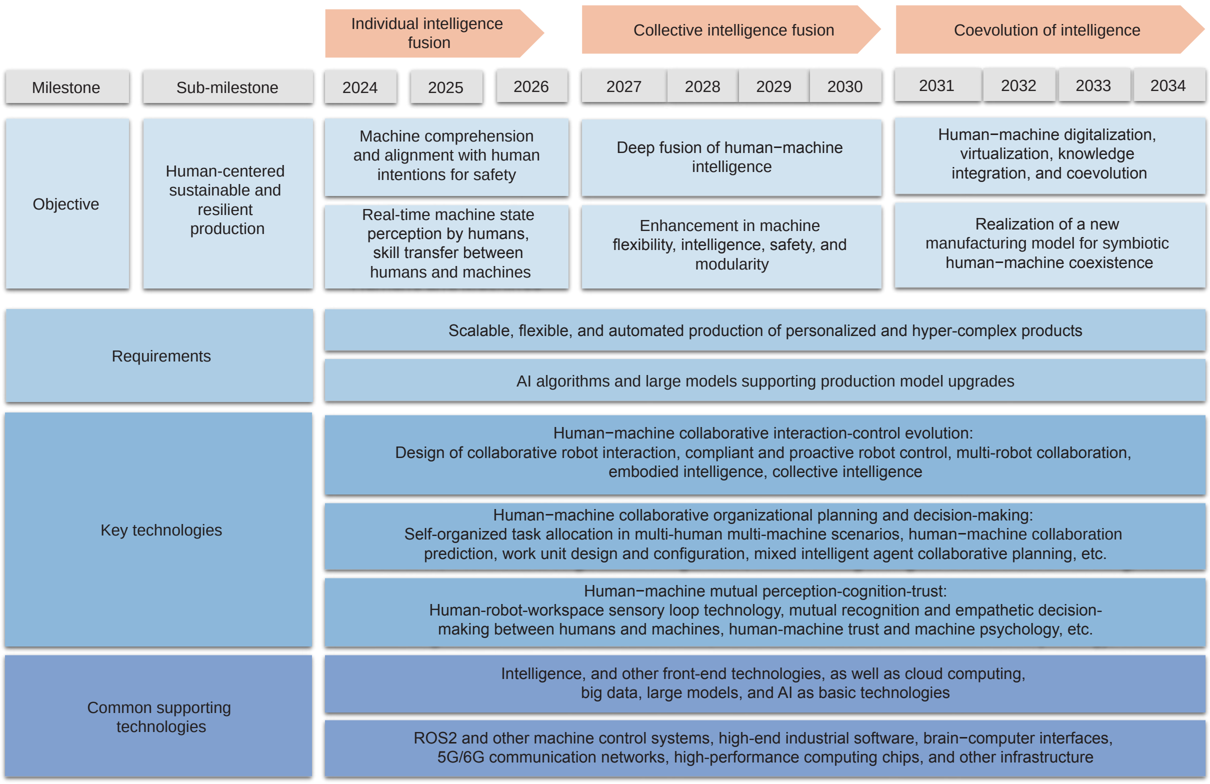

Figure 1.2.3 Roadmap of the engineering research front of “research on human–machine symbiosis intelligent manufacturing under the Industrial 5.0 environment”

with drones (VRP-D), and various aspects of vehicle-drone joint path problems. Addressing limitations such as UAVs’ restricted flying distance due to battery capacity and shorter flight ranges, researchers have turned their attention to joint delivery route planning involving both vehicles and drones. This approach leverages the advantages of both ground vehicles and aerial drones. This has resulted in the formulation of multiple problem models, including vehicle-assisted drones, drone-assisted vehicles, independent delivery, and parallel delivery. Current research incorporates multiple objective optimizations, considering factors such as cost, path efficiency, time windows, energy consumption, and carbon emissions. In addition to drawing from classical path-planning techniques, contemporary studies integrate dynamic factors found in urban settings, such as flight restrictions, public safety and privacy concerns, and changes in demand for last-mile delivery. This integration ensures more practical and feasible outcomes, signifying the future trajectory of UAV logistics delivery path research.

(2) Drone scheduling challenges

Drone scheduling builds upon path planning and focuses on the real-time allocation of multi-drone delivery tasks and the arrangement of ground support resources. The process involves comprehensive considerations of factors such as available delivery time, support facility capacity, and charging station layout. This includes mixed scheduling involving both vehicles and drones, scheduling for drone fleets, and the optimization of charging stations, warehouses, and take-off and landing facility layouts. Recent studies have introduced unpredictable urban environmental factors such as wind fields, tall obstructions, no-fly zones, and risks associated with falling objects into constraint conditions. In the future, integrating variables such as logistics warehouse locations, fleet size, battery charging, nonlinear energy consumption, and drone malfunctions into more complex scheduling optimization models will likely become new research foci.

(3) Trajectory optimization and operational management

Unlike path planning, which focuses on two-dimensional route design, trajectory optimization is concerned with designing three-dimensional space trajectories. Optimization models aim not only to minimize flight time and energy consumption but also to accommodate constraints imposed by various air restriction zones and ground obstacles. Operational management research delves into factors influencing UAV logistics, encompassing policy, technological environments, market size, business models, and more.

Algorithms addressing the aforementioned logistics delivery path and scheduling optimization challenges can be categorized into two main types: exact algorithms and heuristic algorithms. Exact algorithms and solvers are commonly applied for precise solutions to small-scale problems, while heuristic algorithms are employed for nearly optimal solutions to larger-scale problems. The research focused of heuristic algorithms centers on solution quality, convergence speed, and potential for improvement. As model complexity increases, enhancing algorithm efficiency and accuracy becomes a renewed priority. As the field advances, establishing systems for validating algorithms will emerge as a new research area.

Electrically driven zero-emission drones align seamlessly with sustainable development trends. Research evaluating logistics carbon emissions from a socioecological perspective represents a prominent current research direction. The assessment typically involves ground trucks, electric vehicles, and motorcycles. For UAV logistics transportation, a new research direction revolves around the "green routing" problem, aiming to reduce CO_2 emissions from combined vehicle-drone delivery systems. Future exploration may also delve into incorporating clean energy sources such as solar and wind power into the charging network, as well as investigating the relationship between drone delivery system efficiency and charging layout. Additionally, due to drones flying at low altitudes, issues such as noise pollution, risks from falling objects, and infringement of public privacy also hold significant research value.

In the front of "research on unmanned aerial vehicle dispatching and path optimization in logistics", the countries with the highest core paper counts are the USA, China, and Germany (Table 1.2.5). Noteworthy producing institutions include Northeastern University, Massachusetts Institute of Technology, and Portland State University (Table 1.2.6). Analyzing major country collaboration networks (Figure 1.2.4), there is substantial collaboration between Canada, the USA, China, and other nations. Within major institution collaboration networks (Figure 1.2.5), close collaboration is observed between institutions such as Northeastern University, Massachusetts Institute of Technology (MIT), and Binghamton University in the USA. As highlighted in Table 1.2.7, China leads in citing paper count. Likewise, Table 1.2.8 demonstrates that the institutions with the

Table 1.2.5 Countries with the greatest output of core papers on "research on unmanned aerial vehicle dispatching and path optimization in logistics"

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	USA	17	37.78	1 641	96.53	2019.2
2	China	5	11.11	444	88.80	2019.0
3	Germany	4	8.89	294	73.50	2018.2
4	Turkey	3	6.67	481	160.33	2018.0
5	Singapore	3	6.67	309	103.00	2019.3
6	Italy	3	6.67	295	98.33	2019.0
7	Canada	3	6.67	250	83.33	2019.0
8	India	3	6.67	169	56.33	2020.0
9	Denmark	2	4.44	206	103.00	2018.0
10	Spain	2	4.44	201	100.50	2019.5

Table 1.2.6 Institutions with the greatest output of core papers on "research on unmanned aerial vehicle dispatching and path optimization in logistics"

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Northeastern University, USA	3	6.67	231	77.00	2020.7
2	Massachusetts Institute of Technology	3	6.67	223	74.33	2020.0
3	Portland State University	3	6.67	218	72.67	2018.7
4	National University of Singapore	2	4.44	259	129.50	2019.5
5	Friedrich Schiller University Jena	2	4.44	177	88.50	2019.5
6	State University of New York at Binghamton	2	4.44	111	55.50	2020.0
7	Institute of Science and Technology of Porto	1	2.22	564	564.00	2017.0
8	University of Trás-os-Montes and Alto Douro	1	2.22	564	564.00	2017.0
9	Galatasaray University	2	6.90	71	35.50	2022.0
10	Catholic University of Leuven	1	3.45	281	281.00	2019.0

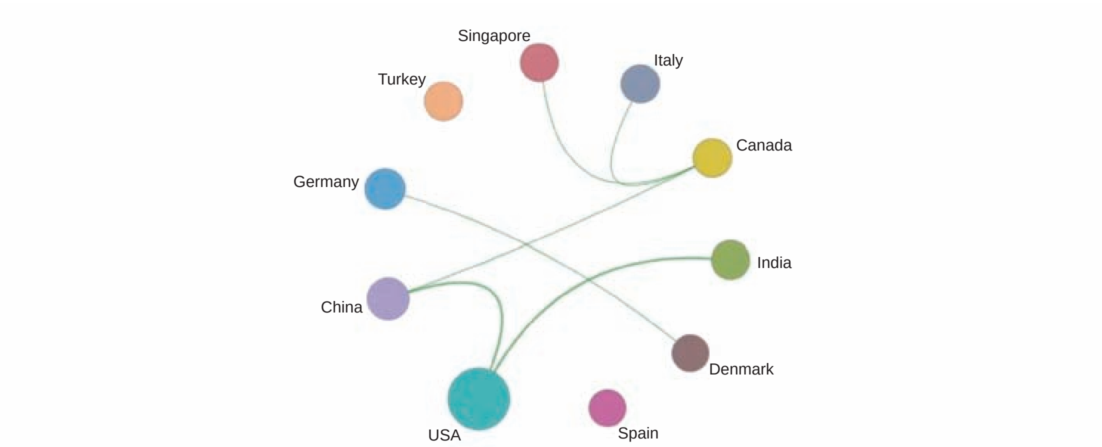

Figure 1.2.4 Collaboration network among major countries in the engineering research front of "research on unmanned aerial vehicle dispatching and path optimization in logistics"

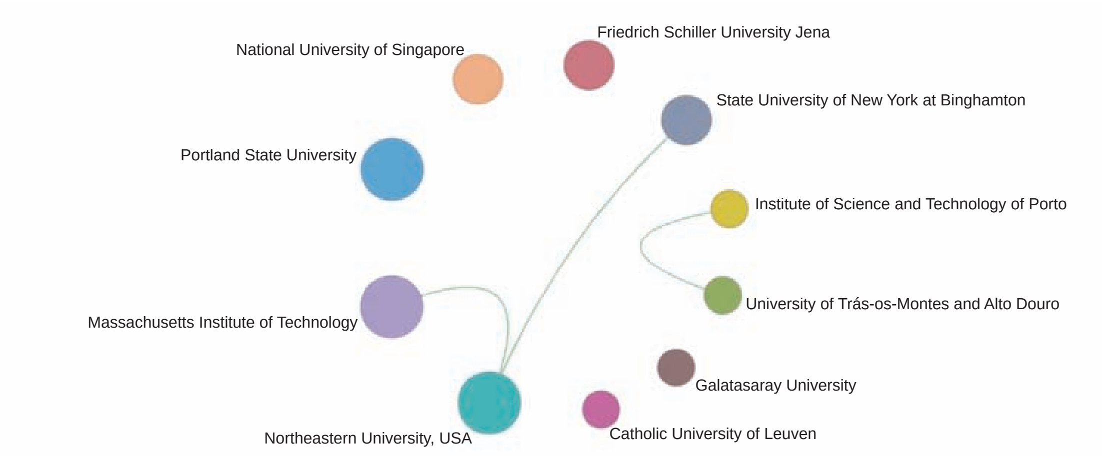

Figure 1.2.5 Collaboration network among major institutions in the engineering research front of "research on unmanned aerial vehicle dispatching and path optimization in logistics"

Table 1.2.7 Countries with the greatest output of citing papers on "research on unmanned aerial vehicle dispatching and path optimization in logistics"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	98	24.69	2020.3
2	USA	82	20.65	2019.9
3	UK	46	11.59	2020.1
4	Germany	27	6.80	2019.7
5	Republic of Korea	26	6.55	2019.7
6	France	24	6.05	2020.0
7	Italy	23	5.79	2020.2
8	Spain	22	5.54	2019.4
9	India	18	4.53	2020.7
10	Canada	16	4.03	2020.5

Table 1.2.8 Institutions with the greatest output of citing papers on "research on unmanned aerial vehicle dispatching and path optimization in logistics"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Sejong University	6	13.95	2021.8
2	Chinese Academy of Sciences	5	11.63	2021.6
3	University of Derby	4	9.30	2021.5
4	Southeast University	4	9.30	2020.8
5	National University of Singapore	4	9.30	2022.0
6	Hong Kong Polytechnic University	4	9.30	2021.2
7	Zhejiang University	4	9.30	2022.0
8	University of Macau	3	6.98	2021.7
9	Rongxuan University	3	6.98	2022.0
10	Kyung Hee University	3	6.98	2021.3

highest citing paper counts are Sejong University in Republic of Korea, Chinese Academy of Sciences, and University of Derby in the UK. Figure 1.2.6 visually represents the developmental trajectory in the front of "research on unmanned aerial vehicle dispatching and path optimization in logistics".

1.2.3 Research on the symbiotic logic and governance of major engineering innovation ecosystems

In light of the current state of research and practical management of mega-projects, the frontier areas of study in the symbiotic logic and governance of mega-project innovation ecosystems primarily include the following two aspects.

(1) Symbiotic evolution and value co-creation in mega-project innovation ecosystems

In recent years, the challenges associated with technological innovation in the context of mega-projects have been escalating. On

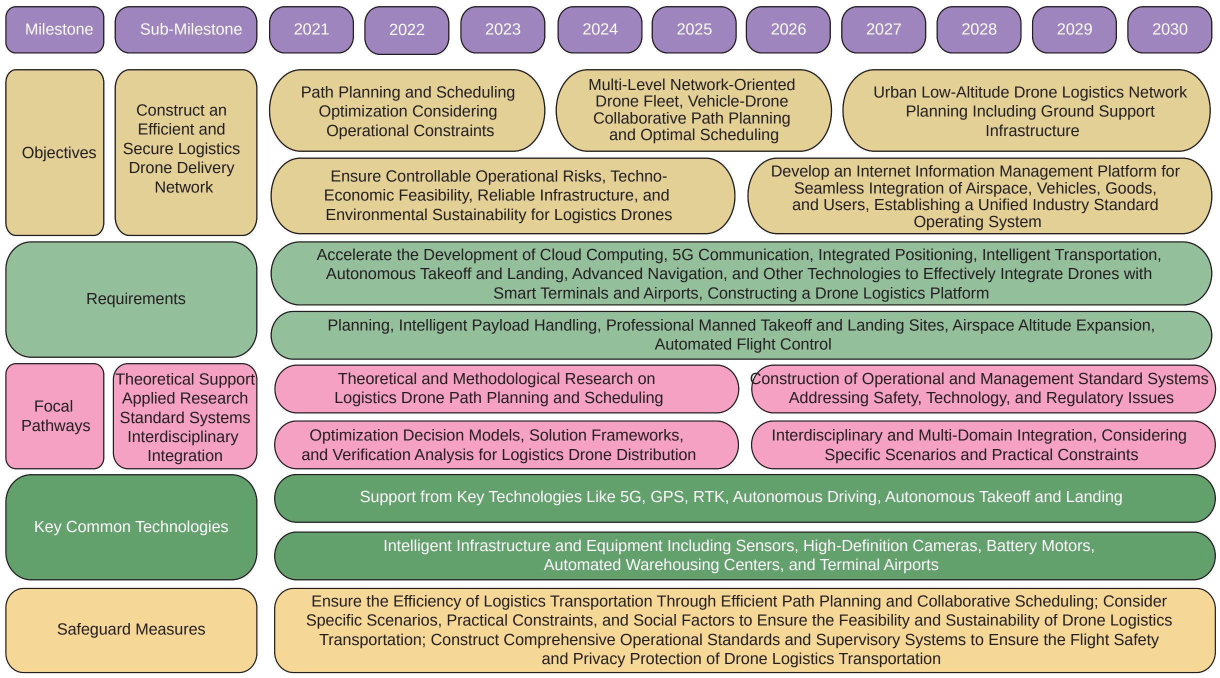

Figure 1.2.6 Roadmap of the engineering research front of “research on unmanned aerial vehicle dispatching and path optimization in logistics”

one hand, the diversified demands of various stakeholders, the transformative impact of emerging technologies, and the trend towards digital empowerment have accentuated the strategic importance of innovation in mega-projects, rendering it a critical determinant of project success. On the other hand, innovation activities within mega-projects confront a unique set of challenges, including distinct innovation contexts, rigid target requirements, dynamic phase evolution, and complex technological integration, which involve managerial issues divergent from those in conventional corporate technological innovation. In light of these considerations, the focal point of research in mega-project innovation management needs to shift from traditional technological innovation systems to innovation ecosystems.

An innovation ecosystem is a vibrant and evolving platform formed based on engineering innovation practices. It integrates the origins and processes of innovation, the participating actors and environmental elements, and the aggregation of resources and emergence of force fields into a systemic framework. This ecosystemic approach holds the potential to overcome the limitations of singular, linear, static, and closed research paradigms. The formation of such an ecosystem is predicated upon the establishment of relationships among various actors within the system, resulting in a tightly interconnected and co-evolving entity. These actors collaborate based on a consensus for value co-creation, thereby forming a value community.

In relation to the symbiotic evolution and value co-creation within mega-project innovation ecosystems, several research questions warrant further exploration: the self-organization and inter-organizational learning aimed at enhancing innovation capabilities in mega-projects; the dynamic evolutionary mechanisms of mega-project innovation ecosystems; the behavioral patterns of value co-creation within mega-project innovation ecosystems under the backdrop of digital transformation; and the orchestration and allocation of resources and value in mega-project innovation ecosystems based on symbiotic and mutually beneficial relationships.

(2) Governance mechanisms in mega-project innovation ecosystems

Compared to conventional projects, mega-projects exhibit multi-dimensional, multi-level, and multi-phase complexities, and their management practices face a myriad of intricate challenges. Given the need to marshal resources for problem-solving within a constrained timeframe, the governance of mega-projects is often closely associated with national systems. Consequently, governance research for mega-projects primarily revolves around specific aspects or systemic mechanisms, such as the “corporate-government–society” governance framework oriented towards social responsibility in mega-projects, or the “government–market” dual governance mechanisms targeting organizational models in mega-projects. The fundamental components of an innovation ecosystem are species (innovation actors), which form various communities through connections. These species and communities drive the overall evolution of the system through symbiotic competitive cooperation. Therefore, governance aimed at mega-project innovation ecosystems should adopt a complex systems perspective, combining the interactive relationships and deep characteristics among different types of innovation actors to design targeted governance strategies. This promotes the efficient and coordinated symbiotic evolution of the mega-project innovation ecosystem, forming a crucial platform that supports high-quality, high-level, and high-impact innovation outcomes, diffusion, and transformation. Currently, several research questions requiring further exploration include: the co-evolutionary governance of mega-project innovation ecosystems; governance of mega-project innovation ecosystems under a national system; and platform governance strategies for mega-project innovation ecosystems.

Existing research indicates that in the front of “research on the symbiotic logic and governance of major engineering innovation ecosystems”, the top three countries in terms of the number of core papers are China, the UK, and Australia, as shown in Table 1.2.9. The countries with the highest citations per paper are Singapore, Australia, and the USA (Table 1.2.9). Within the network of core paper-producing countries (Figure 1.2.7), Chinese scholars have extensive collaborations with their counterparts in Australia, the USA, and the Netherlands. Specifically, Chinese scholars have constructed theoretical frameworks for the formation, evolution, and governance of mega-project innovation ecosystems, drawing upon significant projects such as the Hong Kong-Zhuhai-Macau Bridge. These frameworks delineate the role of ecosystem integrators and elucidate the mechanisms for value co-creation within innovation ecosystems. Relying on major projects like the London Underground, Heathrow Airport Terminal, and the Bang Na Expressway, international scholars have explored various facets of mega-project innovation ecosystems, including significance construction, “windows of opportunity”, incremental and open innovation, and cross-organizational learning.

In the front of “research on the symbiotic logic and governance of major engineering innovation ecosystems”, the top three institutions in terms of the number of core papers are Tongji University, University College London, and Shanghai Jiao Tong University (Table 1.2.10). Within the network of core publication-producing institutions (Figure 1.2.8), collaborations are particularly frequent among Tongji University, Chongqing University, and Huazhong Agricultural University, as well as between Aalto University and the University of Oulu. Table 1.2.11 reveals that China, the UK, and Australia lead in the number of citing papers. Table 1.2.12 shows that the top three institutions in terms of the number of citing papers are Tongji University, University

Table 1.2.9 Countries with the greatest output of core papers on “research on the symbiotic logic and governance of major engineering innovation ecosystems”

No.	Country	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	China	21	46.67	397	18.90	2020.4
2	UK	12	26.67	241	20.08	2020.2
3	Australia	6	13.33	311	51.83	2018.0
4	USA	4	8.89	192	48.00	2017.8
5	Finland	4	8.89	106	26.50	2019.8
6	Germany	2	4.44	62	31.00	2019.0
7	Canada	2	4.44	60	30.00	2020.0
8	Norway	2	4.44	20	10.00	2021.0
9	Netherlands	2	4.44	8	4.00	2021.5
10	Singapore	1	2.22	57	57.00	2018.0

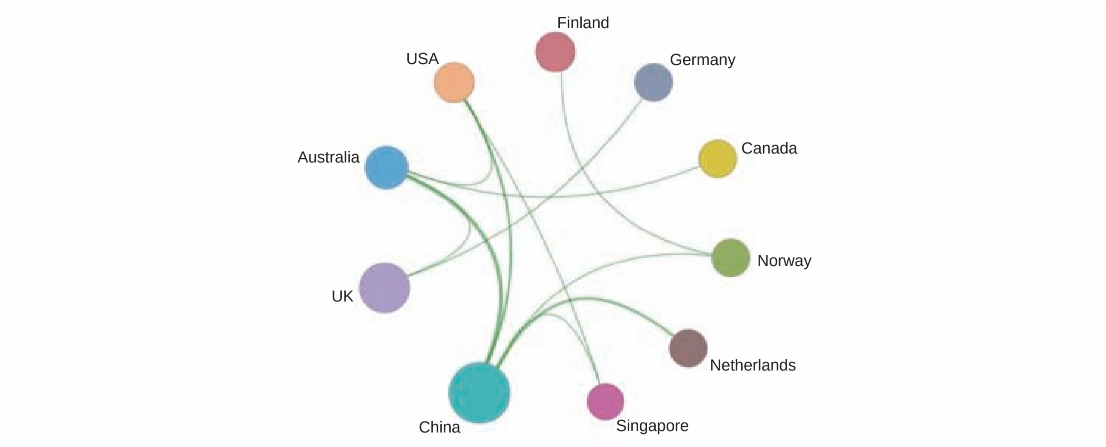

Figure 1.2.7 Collaboration network among major countries in the engineering research front of “research on the symbiotic logic and governance of major engineering innovation ecosystems”

Table 1.2.10 Institutions with the greatest output of core papers on “research on the symbiotic logic and governance of major engineering innovation ecosystems”

No.	Institution	Core papers	Percentage of core papers/%	Citations	Citations per paper	Mean year
1	Tongji University	9	20.00	180	20.00	2020.3
2	University College London	4	8.89	143	35.75	2018.8
3	Shanghai Jiao Tong University	3	6.67	162	54.00	2019.0
4	Aalto University	3	6.67	98	32.67	2019.3
5	Chongqing University	3	6.67	24	8.00	2021.3
6	Nanjing University	2	4.44	76	38.00	2020.5
7	University of Leeds	2	4.44	55	27.50	2020.5
8	University of Oulu	2	4.44	49	24.50	2019.5
9	Huazhong Agricultural University	2	4.44	47	23.50	2019.5
10	University of Sussex	2	4.44	30	15.00	2020.5

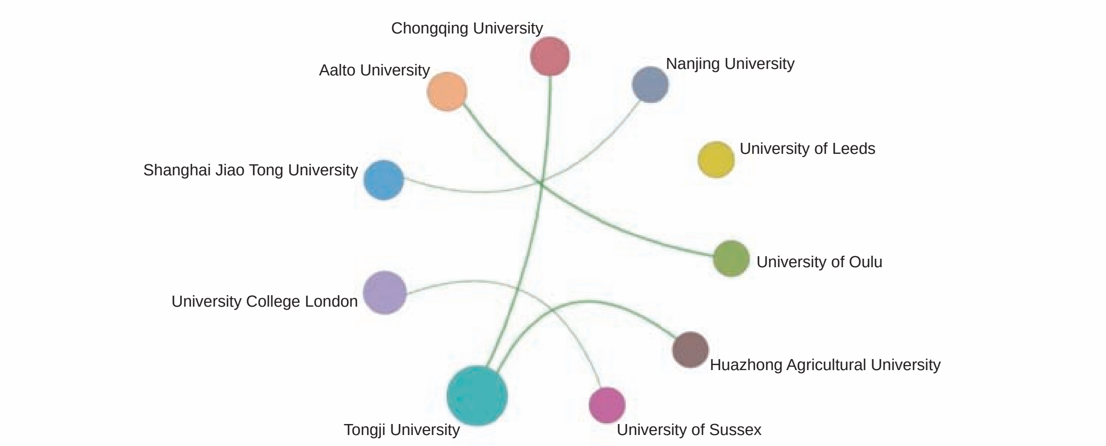

Figure 1.2.8 Collaboration network among major institutions in the engineering research front of “research on the symbiotic logic and governance of major engineering innovation ecosystems”

Table 1.2.11 Countries with the greatest output of citing papers on "research on the symbiotic logic and governance of major engineering innovation ecosystems"

No.	Country	Citing papers	Percentage of citing papers/%	Mean year
1	China	233	34.37	2021.1
2	UK	108	15.93	2020.6
3	Australia	101	14.90	2020.6
4	USA	60	8.85	2021.0
5	Italy	33	4.87	2021.7
6	Canada	29	4.28	2021.0
7	India	25	3.69	2021.2
8	Finland	25	3.69	2021.0
9	Norway	25	3.69	2020.4
10	Netherlands	22	3.24	2021.4

Table 1.2.12 Institutions with the greatest output of citing papers on "research on the symbiotic logic and governance of major engineering innovation ecosystems"

No.	Institution	Citing papers	Percentage of citing papers/%	Mean year
1	Tongji University	45	19.91	2021.0
2	University College London	27	11.95	2020.2
3	Shanghai Jiao Tong University	26	11.50	2020.9
4	University of Leeds	22	9.73	2020.8
5	The Hong Kong Polytechnic University	19	8.41	2020.6
6	Chongqing University	18	7.96	2021.6
7	Politecnico di Milano	15	6.64	2021.8
8	Nanjing Audit University	14	6.19	2021.0
9	University of Technology Sydney	14	6.19	2020.3
10	Deakin University	13	5.75	2020.5

College London, and Shanghai Jiao Tong University. Figure 1.2.9 outlines the developmental trajectory of the front of "research on the symbiotic logic and governance of major engineering innovation ecosystems".

2 Engineering development fronts

2.1 Trends in Top 10 engineering development fronts

In the domain of engineering management, the top ten global fronts in engineering development for the current year include "linear and integer programming solvers", "intelligent factory operation and maintenance systems based on industrial internet and big data", "methods and systems for automatic building design generation based on deep learning", "smart home health care systems for the elderly", "comprehensive urban safety risk monitoring and early warning platform", "supply chain risk management

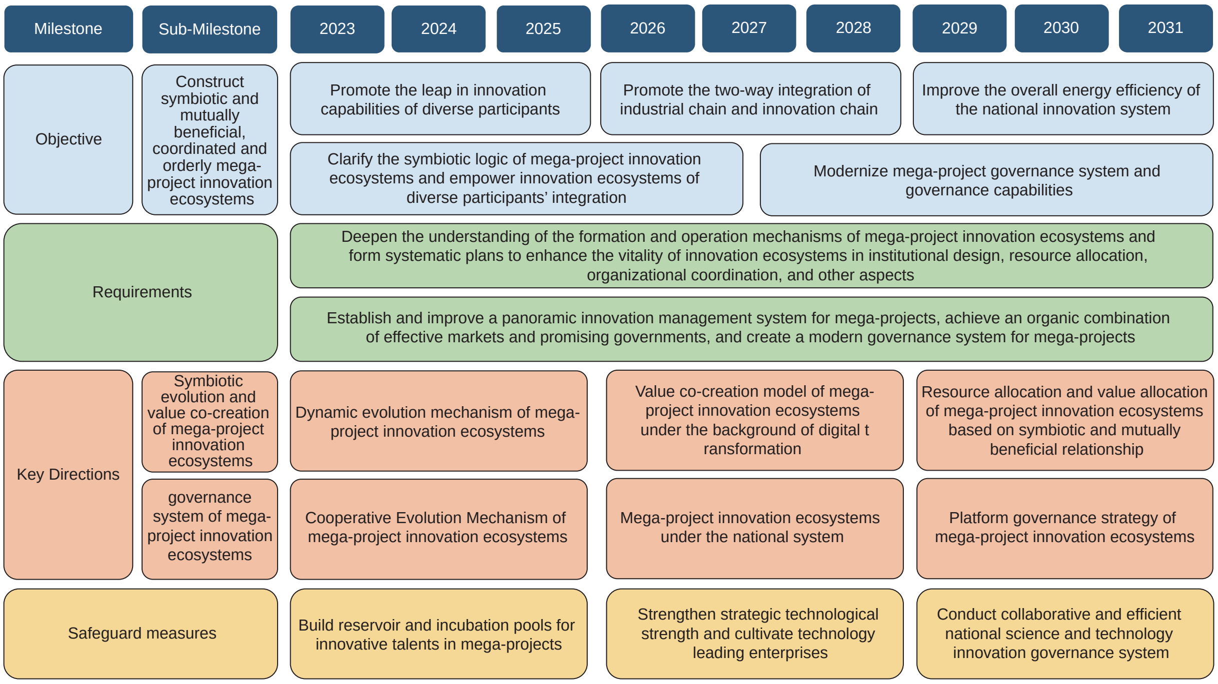

Figure 1.2.9 Roadmap of the engineering research front of "research on the symbiotic logic and governance of major engineering innovation ecosystems"

platform based on intelligent simulation", "industrial equipment health monitoring and data fusion analysis system", "prediction and early warning system for external shocks and internal disturbances in energy systems", "financial risk management system based on federated learning", and "network audio-visual recommendation algorithms and content supervision intelligent platform". The core patent statuses for these fronts are detailed in Tables 2.1.1 and 2.1.2. These ten engineering development fronts span a multitude of disciplines, including medicine, architecture, transportation, and computer science. Among them, "linear and integer programming solvers", "intelligent factory operation and maintenance systems based on industrial internet and big data", and "methods and systems for automatic building design generation based on deep learning" are identified as the focal fronts. Subsequent sections will provide a comprehensive analysis of their current developmental trajectories and future trends.

(1) Linear and integer programming solvers

Linear and integer programming solvers, utilized as engineering software, employ mathematical optimization algorithms to address extensive and intricate challenges faced by public institutions and commercial organizations. This technology has garnered widespread application across defense, energy, manufacturing, transportation, communications, finance, and other sectors, yielding substantial value. The research and development of these solvers demand elevated expertise in mathematical optimization theory and large-scale computer system engineering, combined with significant investments in time and capital, thereby presenting substantial risks. At present, the global dominant market for solvers is monopolized byproducts from three American companies (IBM, Gurobi, and FICO) with formidable barriers to market entry.

Since 2018, Chinese domestic research teams have sequentially introduced indigenous solvers, including the Chinese Academy of Sciences' open-source solver CMIP, Shanshu Technology's COPT, Alibaba Cloud's MindOPT, and Huawei's Tianchou (OPTV) solver, among others. Over the span of three decades of solver product development, research teams worldwide have consistently elevated performance, thereby enhancing computational efficiency and the aptitude to solve large-scale problems. Traditional solver advancement has predominantly relied upon mathematical programming theory and algorithms such as the simplex method, dual theory, branch-and-bound method, and heuristic algorithms, among others.

Table 2.1.1 Top 10 engineering development fronts in engineering management

No.	Engineering development front	Published patents	Citations	Citations per patent	Mean year
1	Linear and integer programming solvers	103	328	3.18	2020.3
2	Intelligent factory operation and maintenance systems based on industrial internet and big data	66	1 090	16.52	2020.9
3	Methods and systems for automatic building design generation based on deep learning	26	208	8.00	2020.0
4	Smart home health care systems for the elderly	53	177	3.34	2019.8
5	Comprehensive urban safety risk monitoring and early warning platform	94	237	2.52	2020.6
6	Supply chain risk management platform based on intelligent simulation	59	334	5.66	2020.9
7	Industrial equipment health monitoring and data fusion analysis system	23	379	16.48	2020.4
8	Prediction and early warning system for external shocks and internal disturbances in energy systems	16	121	7.56	2020.2
9	Financial risk management system based on federated learning	35	74	2.11	2021.5
10	Network audio-visual recommendation algorithms and content supervision intelligent platform	15	196	13.07	2019.1

Table 2.1.2 Annual number of core patents published for the Top 10 engineering development fronts in engineering management

No.	Engineering development front	2017	2018	2019	2020	2021	2022
1	Linear and integer programming solvers	6	15	9	16	24	8
2	Intelligent factory operation and maintenance systems based on industrial internet and big data	0	1	8	13	20	16
3	Methods and systems for automatic building design generation based on deep learning	1	4	5	7	2	34
4	Smart home health care systems for the elderly	4	11	11	5	8	13
5	Comprehensive urban safety risk monitoring and early warning platform	9	4	10	8	22	10
6	Supply chain risk management platform based on intelligent simulation	4	3	0	7	17	9
7	Industrial equipment health monitoring and data fusion analysis system	3	0	2	5	5	31
8	Prediction and early warning system for external shocks and internal disturbances in energy systems	2	2	1	3	2	66
9	Financial risk management system based on federated learning	0	0	0	4	9	30
10	Network audio-visual recommendation algorithms and content supervision intelligent platform	2	6	1	3	0	28

However, recent technological breakthroughs in computing, coupled with the evolution of artificial intelligence and machine learning algorithms, have introduced fresh avenues for research in the realm of linear and integer programming solvers. These avenues encompass but are not confined to large-scale distributed parallel computing, artificial intelligence, and quantum computing. Current developmental trajectories primarily center around expeditiously resolving extensive and intricate challenges to furnish superior global optimization decisions for institutions and corporations, augmenting their capacity to respond to unforeseeable changes.

(2) Intelligent factory operation and maintenance systems based on industrial internet and big data

As the industrial internet and big data technology continue to advance and deeply integrate with the manufacturing sector, intelligent factories have emerged, facilitating a close connection and interaction among production equipment, sensors, and other industrial components. The real-time collection, sharing, and analysis of extensive production data have become feasible. In this context, the maintenance management model within factories has progressively transitioned toward digitization, networking, and intelligence. This evolution has given rise to intelligent factory maintenance systems that are grounded in the comprehensive interconnection of people, machines, materials, methods, and the environment. These systems are supported by the collection and management of production data throughout the entire lifecycle. Leveraging artificial intelligence tools, this system can perform real-time monitoring of production processes, precisely manage equipment statuses, and intelligently issue maintenance instructions. Consequently, a new service-oriented maintenance system has been established, extending across the entire industrial and value chains.

The present research emphasizes several key areas: enhancing data management linkage, precision, and timeliness within the maintenance system; improving equipment control accuracy and responsiveness; and enhancing system operational reliability and integration. To achieve these goals, there is a strong emphasis on industrial big data collection and management technology, equipment fault diagnosis and maintenance technology driven by industrial big data, and technological integration and development at the system level.

However, challenges persist for intelligent factory maintenance systems, including insufficient levels of intelligence, high integration difficulty, and stringent data security requirements. As a result, there is a need for demand-driven custom development of maintenance systems, exploration of multisource heterogeneous data fusion technology, and optimization of encryption and authentication technology. These areas are likely to emerge as central focal points for future research and development efforts.

(3) Methods and systems for automatic building design generation based on deep learning

The automatic generation of architectural schemes entails the computer-based creation of architectural design concepts and plans. This process occurs through automated means, relying on factors such as project background, design objectives, and requirements. Parametric design technology plays a role in realizing this process. However, the resultant architectural schemes are contingent upon parametric models constructed independently by designers, thereby constraining the level of automation and intelligence achievable. While existing architectural design materials encapsulate designers' experience and expertise, their potential has not been fully harnessed in previous research due to their intricate attributes. These attributes encompass multidisciplinary intersections, diverse forms, and pronounced timeliness.

With the progressive enhancement of deep learning technology's capacity to extract features from multidimensional, multimodal, and multiscale data, approaches and systems for automatically generating architectural schemes, propelled by deep learning, have emerged as a pivotal driving force, a significant avenue, and a novel platform for expediting the intelligent transformation and advancement of the architectural design industry. Architectural design drawings constitute the core content within existing design materials and serve as the principal visual mode for presenting design concepts.

Recent scholarly investigations have drawn inspiration from thought paradigms within the realm of computer-generated imagery, with a specific focus on architectural scheme design. Key discussions have revolved around semantic representation of architectural schemes, architectural style transfer, amalgamation of multimodal features within architectural design, applications and refinements of deep generative models, as well as automated compliance assessments.

To further bolster the dependability of automatically generated architectural schemes and elevate the general level of intelligence within design systems, upcoming predominant research trajectories will encompass human–machine collaborative design modes that harmonize regularity and creativity. Additionally, research will delve into enhancing design data driven by intricate architectural parametric models, recognizing and autonomously verifying ambiguous design specifications, and cultivating methods and systems for generating architectural schemes that seamlessly integrate multidisciplinary engines and design principles.

(4) Smart home health care systems for the elderly

With the rapid proliferation of “inverted pyramid” and “empty nest” family structures, as well as a growing number of aging individuals with disabilities, the challenge posed by an aging population is intensifying. As of the conclusion of 2022, the demographic of individuals aged 65 and above has swelled to 210 million, constituting 14.9% of the total population. More than half of this group resides without children at home, a circumstance that thrusts many elderly individuals into the sphere of at-home care. To combat this predicament, the Intelligent Health Home Care System for the Elderly platform harmonizes contributions from medical institutions, communities, and corporations. It leverages advanced technologies such as the Internet of Things, cloud computing, big data, and artificial intelligence to comprehensively cater to the elderly’s requirements for at-home care.

The key research directions encompass: ① the development of innovative intelligent perception and real-time monitoring technologies; ② the creation of disease and risk prediction and management systems; ③ the establishment of intelligent early-warning and online diagnosis systems; and ④ the formulation of intelligent home interconnection systems.

Looking ahead, as the next wave of intelligent technology emerges and elderly home care becomes increasingly sophisticated, augmenting the comprehensiveness, precision, diversity, and integration of services will emerge as the industry’s future trends. These trends will interlace aspects of medical care, eldercare, community engagement, commerce, and governmental intervention, establishing an integrated platform for living, medical assistance, well-being, and recreational services. Precision advancement will harness emerging data analysis and artificial intelligence technologies to yield more precise prognostications and evaluations of the elderly’s health status. Diversified services will underscore individual distinctions and multifarious needs, catering to the varied and personalized requisites of the elderly to amplify their quality of life during later stages. Integrative development will spur the amalgamation and dissemination of technology and resources across various domains, leading to more effective and all-encompassing home care services.

(5) Comprehensive urban safety risk monitoring and early warning platform

The Integrated Urban Safety Risk Monitoring and Early Warning Platform refers to a digital infrastructure designed from a strategic perspective of overall urban safety and large-scale emergency response. This platform leverages modern information technologies such as the Internet of Things, cloud computing, big data, and artificial intelligence to construct a network that supports urban safety risk monitoring, disaster situational awareness, intelligent risk assessment, early warning, and coordinated response. It focuses on various types of risks, including natural disasters, public health incidents, accidental catastrophes, social safety events, and macro-environmental factors. The aim is to elevate the level of intelligent identification, prevention, mitigation, and management of urban risks, thereby ensuring the secure development of cities. Currently, the Integrated Urban Safety Risk Monitoring and Early Warning Platform in China has entered the pilot construction phase. However, rapid urbanization has led to an increase in urban population and an expansion of infrastructure systems, making urban systems increasingly complex. Concurrently, the frequency of extreme events under climate change, the aggregation of multiple types of disasters, and the prominence of disaster chains have escalated the composite and systemic safety risks that cities face. Against this backdrop, the construction and developmental directions of the Integrated Urban Safety Risk Monitoring and Early Warning Platform include: refining cross-departmental and cross-regional data sharing and coordinated response mechanisms; researching comprehensive urban sensing technologies that mutually calibrate the accuracy of space-based, aerial-based, and ground-based monitoring; employing advanced technologies such as artificial intelligence and digital twins to develop precise and intelligent identification, assessment, and prediction technologies for urban safety risks, particularly for multi-type cascading coupled risks; enhancing the dissemination of early warning information through multiple means, channels, and audiences; and improving the intrinsic resilience of monitoring and early warning hardware facilities, as well as strengthening the platform’s capabilities in information security risk prevention and control.

(6) Supply chain risk management platform based on intelligent simulation

Presently, the robust advancement of digitization and globalization has ushered in an abundance of data, information, and emerging technological resources to fortify supply chains. However, this progress simultaneously engenders heightened complexity within supply chains, accentuating uncertainty and escalating risk levels, all while hastening market fluctuations. This increasingly intricate and unsettled milieu presents more profound trials to the realm of supply chain risk management. In the era of digitalization, intelligent simulation research methods find themselves uniquely positioned to address these challenges.

The Intelligent Simulation-Based Supply Chain Risk Management Platform offers distinct advantages. By crafting a virtual supply chain environment, this platform not only mimics existing supply chain strategies but also models the behaviors, decisions, interactions, and potential occurrences and propagation of risk events among diverse participants. This enables a more precise emulation of the supply chain's intricacy, dynamism, and variability. Consequently, decision-makers are empowered to assess the impact of various risks on the supply chain and formulate corresponding strategies for risk response.

This platform showcases innovative features such as diverse risk event modeling, decision support, multiscale simulation, and collaborative decision-making. Its applications span risk assessment and prognostication, supply chain adaptation and optimization, emergency response planning, and risk management training and drills. Additionally, intelligent simulation systems frequently encompass distributed simulation models capable of functioning across assorted network environments, including cloud setups. This architecture permits agents to opt for residency or movement on distinct server platforms based on the available computational load, thus facilitating comprehensive, detailed simulations of large-scale supply chains and system-wide computational enhancements.

In the days ahead, the Intelligent Simulation-Based Supply Chain Risk Management Platform is poised to assimilate more advanced artificial intelligence technologies such as machine learning and deep learning. This integration aims to bolster the precision and timeliness of risk prediction. Simultaneously, the platform is progressing toward heightened customization to cater to the specific requisites of diverse industries, companies, and risk scenarios. This trajectory will provide users with personalized analysis and decision-making support. In essence, the Intelligent Simulation-Based Supply Chain Risk Management Platform is slated for rapid evolution, swiftly becoming an indispensable instrument in the digital era for effective supply chain risk management.

(7) Industrial equipment health monitoring and data fusion analysis system

The Industrial Equipment Health Monitoring and Data Fusion Analysis System harnesses advanced sensing, 5G technology, artificial intelligence algorithms, and expert systems. It seamlessly integrates cloud computing, fog computing, edge computing, and other data processing paradigms to achieve real-time perception of the health status of industrial equipment. This approach enables precise fault diagnosis and prediction, thus facilitating the implementation of preemptive maintenance strategies aimed at averting unforeseen breakdowns.

Presently, in the face of intricate industrial equipment structures, varying operational conditions, and limited fault instances, scholars have turned to big data and digital twin technologies to propose novel theories for data generation and fusion analysis. They have also devised methods for fault migration diagnosis and prediction. Correspondingly, they have explored optimal operation and maintenance strategies. This endeavor necessitates the high-level fusion of extensive multimodal monitoring data, entailing the determination of data fusion levels, assessment of priorities for multimodal data fusion, and the incorporation of human factors analysis and decision-making within complex industrial contexts. The ultimate aim is to maximize service availability, curtail unplanned downtime, and diminish operational and maintenance expenses. These objectives guide the formulation of optimal operation and maintenance protocols for industrial equipment.

The swift progress of the Industrial Equipment Health Monitoring and Data Fusion Analysis System has effectively overseen the well-being of high-value-added equipment, encompassing CNC machine tools, aerospace machinery, and industrial robots. This has led to notable economic and societal gains. In the future, this system will emerge as a pioneering frontier in multidisciplinary engineering research and development. This encompasses ensuring the privacy and security of monitoring data for industrial equipment via blockchain technology, executing on-site and off-site joint monitoring and health management founded on digital twin technology, economizing materials and expediting operation and maintenance time through 3D printing of spare parts, deploying generative AI technology to facilitate the formulation of preemptive maintenance strategies, and delving into other groundbreaking possibilities.

(8) Prediction and early warning system for external shocks and internal disturbances in energy systems

Significant emergent events often exert a non-negligible impact on energy security, with both external shocks and internal disturbances concurrently affecting the safety of energy systems. External shocks include energy trade conflicts, major public safety incidents, and geopolitical instability, among others. Internal disturbances include short-term meteorological fluctuations, extreme weather interference, and abnormal operational conditions of facilities. Energy supply and consumption systems of varying structures exhibit corresponding complexity and diversity in the transmission pathways and feedback mechanisms of external shocks and internal disturbances. The impacts on the safe operation of systems manifest significant spatiotemporal heterogeneity. In-depth research is urgently needed in risk measurement, pattern recognition, early warning and prediction, impact assessment, and response strategies.

Primary research directions include: ① meteorological prediction technologies for energy systems; ② transmission mechanisms, evolutionary laws, and diffusion principles of significant emergent events in energy systems; ③ key technologies for early identification and predictive warning of external shocks and internal disturbances in energy systems; ④ coordinated safety warning mechanisms, multi-faceted safety assurance mechanisms, emergency supply mechanisms, and risk response mechanisms for energy systems. Emerging trends in these domains include: ① meteorological disturbance prediction technologies: innovations in ultra-short-term weather forecasting, large-scale long-term wind energy prediction methods, atmospheric circulation stability and disturbance prediction correction techniques, and lightning warning systems; ② early warning mechanisms for energy system shocks: development of key indicator identification and warning systems based on statistical patterns, macro-crisis analysis tools leveraging big data analytics, and risk identification technologies for energy infrastructure based on satellite and remote sensing; ③ research on the diffusion mechanisms of energy system shocks: exploration of dynamic downscaling studies based on climate models and research on climate change transmission pathways informed by global atmospheric models.

(9) Financial risk management system based on federated learning

Federated learning is an algorithmic framework tailored for the construction of machine learning models. Within this framework, multiple data owners collaborate to fulfill the training objectives of machine learning models while upholding the privacy and security of their individual data. The models derived from this joint training can then be shared and adopted by all participating data owners. Throughout the model training process, the original data remain within the custody of the respective data providers, and encrypted information is transferred and exchanged among the involved parties. This methodology yields models whose performance can approximate that of models trained on complete data.

In the realm of financial risk management, financial institutions perpetually strive to amass and scrutinize diverse data sources to mitigate information asymmetry and curtail risk assumptions. However, many data assets crucial for financial risk management cannot be directly harnessed by financial institutions owing to data security and privacy limitations. This impairs the full realization of their commercial value. Federated learning resolves this conundrum by facilitating the integration of financial data with data from various other domains. This synergy fosters the creation of more precise and comprehensive algorithmic models, thereby offering a more holistic perspective for managing financial risks.

Contemporary research predominantly centers on the fusion of data from financial institutions and other enterprises. This fusion is employed for tasks such as constructing investor profiles, evaluating individual credit ratings and repayment capabilities, gauging the operational status and future potential of small and medium-sized enterprises, conducting risk assessments of financiers, developing risk warning models grounded in data related to loan repayment during the loan process, and fostering collaboration among multiple financial institutions for endeavors such as credit card fraud detection, anti-money laundering prewarning, and identification. Moreover, insurance companies are utilizing multiparty data tied to the insured to undertake pricing studies for insurance products.

Anticipated future research trajectories encompass delineating the structure and development model of a federated learning ecosystem tailored for financial risk management. This involves establishing substantial big data platforms tailored for federated learning within the context of financial risk management. Additionally, future research will delve into the selection decisions and measurement of contributions made by diverse data contributors within the framework of federated learning. Methodological advancements will be pursued for applying federated machine learning in financial risk management scenarios. Furthermore, the explainability of financial federated learning models, the creation of expansive financial risk cognitive maps founded on federated learning, and the integration of artificial intelligence generated content (AIGC) within financial vertical domains through federated learning will all likely constitute burgeoning domains of exploration.

(10) Network audio-visual recommendation algorithms and content supervision intelligent platform

Online audio-visual recommendation algorithms are data-driven technologies that predict and match personalized content based on user interests and behavior, thereby fostering the growth of the digital economy. These algorithms analyze user viewing records, searches, and social behavior and recommend content of interest from an extensive array of resources. With technological advancements, algorithms are now able to combine multimodal features, individual attributes, and domain information to attain more accurate personalized recommendations. This enhancement in service quality strengthens the competitiveness of internet platforms. The main aspects of this advancement are as follows:

1) Data analysis techniques: traditional algorithms rely on historical behavior to forecast interests, but the era of big data necessitates the integration of various media forms, such as news and videos. Algorithms that combine multimodal features can analyze associations and provide precise recommendations. Large language models, such as BERT, are applied to recommendation systems, processing multidimensional data, extracting rich semantic information, and offering a comprehensive recommendation experience.

2) Products and services intelligent recommendation techniques: it is vital that algorithms ensure fairness in recommendations, avoiding discrimination and information silos, while promoting positive values. Strategies to increase recommendation diversity, reduce information islands, and safeguard user privacy are crucial. Constructing robust data security measures and personal information protection policies is essential to mitigate information leakage issues.

3) System development for different business scenarios: e-commerce platforms must provide equitable and quality recommendations, avoiding inequality due to divergent consumer capabilities. Video websites should broaden the recommendation information range to prevent user information isolation. Social media platforms need to decrease viewpoint polarization, create accurate recommendation mechanisms, and guide healthy development.

In the global landscape, the USA and China are the main competitors, boasting numerous patents and high citation numbers. China’s Foxconn leads in this field, with Chinese universities emphasizing theoretical innovation, while the industry centers on practical effects. Conversely, the USA is dedicated to enhancing user experience, focusing on personalized content recommendations for mobile intelligent terminals, encompassing deep learning and multimodal recommendation technology.

Future prospects indicate that online audio-visual recommendation algorithms will continue to evolve across various dimensions, reflecting a complex interplay between technology, ethics, commerce, and social considerations.

2.2 Interpretations for three key engineering development fronts

2.2.1 Linear and integer programming solvers

The research focused of linear and integer programming solvers centers on the amalgamation of mathematical programming theory and computer application technology. Mathematical programming theory constitutes the foundational basis of mathematical programming solvers. In 1947, George Dantzig, renowned as the "father of linear programming", introduced the "simplex method", which proficiently addressed linear programming problems. This method later garnered recognition as one of the most significant algorithms of the 20th century. In 1979, L. Khachiyan pioneered the ellipsoid algorithm, providing the inaugural proof that linear programming problems could be solvable in polynomial time. However, its computational efficiency proved inadequate, impeding practical application. In 1984, N. Karmarkar conceived the interior point algorithm, the premier practically applicable polynomial-time algorithm for linear programming. In the realm of integer programming, Ralph E. Gomory unveiled the primary general linear integer programming convergence algorithm, the cutting plane algorithm, in 1958. Subsequent scholars introduced algorithms such as branch and bound, as well as branch and cut. In the 1980s, concurrent with the advancement of computer technology, endeavors emerged to create solver software utilizing computers. The foremost commercial solvers worldwide encompass IBM CPLEX, Gurobi, and FICO Xpress. CPLEX, developed in 1988 by American mathematician Robert Bixby and colleagues, was acquired by ILOG in 1997 and subsequently by IBM in 2009. In 2008, core developers from the CPLEX solver team (Zonghao Gu, Edward Rothberg, and Robert Bixby) founded Gurobi. In 1983, Dash Optimization in Edinburgh created Xpress, which was acquired by the American credit enterprise FICO in 2008. In addition to these commercial solvers, global open-source solvers include Germany's ZIB-developed SCIP, Google's OR-Tools, and the COIN-OR foundation's CBC. In recent times, domestic research groups have introduced self-developed solvers. In 2018, the team led by Dai Yuhong at the Chinese Academy of Sciences introduced the inaugural open-source integer programming solver, CMIP. In 2019, Shanshu Technology launched China's first commercial linear programming solver, COPT. In 2020, Alibaba DAMO Academy's Decision Intelligence Laboratory introduced the commercial solver MindOpt. Huawei debuted the Tianchou (OPTV) AI solver in 2021. As of the conclusion of June 2023, on the solver assessment platform offered by Professor Hans Mittelmann at Arizona State University, Shanshu Technology, Gurobi, and Huawei developed solvers ranked among the top three in linear programming. Notably, Gurobi and Shanshu Technology's solvers ranked first and second, respectively, in integer linear programming evaluation.

During the course of solver development, the augmentation of computer hardware speed and the enhancement of solver algorithm efficiency have consistently elevated the overall efficacy of the solver, facilitating the resolution of increasingly extensive problems. Specifically, advancements in computer hardware speed encompass elevated CPU clock rates, heightened memory bandwidth, enhancements in processor physical architecture, upgrades to instruction sets, integration of multicore and multithreading technology, transition from 32-bit to 64-bit architecture, compiler improvements, and more. Optimization of the efficiency of linear programming and integer programming algorithms predominantly stems from algorithm parallelization (e.g., the barrier algorithm in linear programming, tree searching in MILP) and the application of heuristic integer programming algorithms (such as RINS, local branching, MCF cuts), among others.

Looking forward, with the advent of a new generation of computer technology and the amplification of computing power, research directions meriting attention and strategic planning include the following:

1) Distributed parallel computing: presently, mainstream commercial solvers such as CPLEX and Gurobi can solely accommodate 32-core concurrent computing. Mere augmentation of core numbers does not necessarily translate to enhanced solving efficiency. Future research ought to concentrate on optimizing solver algorithms to fully harness the computational capabilities of thousands of GPU cores in distributed services, thus accelerating the solution of large-scale problems.

2) Artificial intelligence algorithms: in recent years, researchers have endeavored to integrate AI technology into solver optimization algorithms to augment the efficiency of solving linear and integer programming problems. Existing machine learning algorithms necessitate training on existing problems. Further research is imperative to ascertain whether the model can ensure effective problem resolution for general scenarios amidst altering problem characteristics.

3) Quantum computing: quantum optimization, a burgeoning area in the realm of quantum computing, has garnered attention. It revolves around leveraging quantum computing to expedite optimization problem solving. Presently, for constrained optimization problems, quantum optimization theories encompass quantum simulated annealing, quantum interior-point methods, quantum linear programming, quantum semidefinite programming, and more. These theories await further validation subsequent to practical implementation of quantum computers.

In addition to linear and integer programming, which are the two most prevalent problems in practical applications, contemporary mathematical programming solvers are also dedicated to addressing more intricate problems. These encompass quadratic programming, second-order cone programming, semidefinite programming, mixed-integer nonlinear programming, and others.

Within the realm of the engineering research front of "linear and integer programming solvers" , the leading three countries in terms of core patent numbers are China, the USA, and Japan (Table 2.2.1). Pertaining to collaborative networks among these principal countries, cooperative efforts are observed between China and Germany, the USA, and the UK, as well as among the USA, the UK, France, and China (Figure 2.2.1). The main output organizations of the core patents include International Business Machines Corporation (IBM), State Grid Electronic Commerce Co., Ltd. and others (Table 2.2.2), etc., where State Grid Electronic Commerce Co., Ltd. and Tsinghua University have some cooperation (Figure 2.2.2).

Table 2.2.1 Countries with the greatest output of core patents on "linear and integer programming solvers"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	61	59.22	182	55.49	2.98
2	USA	26	25.24	75	22.87	2.88
3	Japan	8	7.77	8	2.44	1.00
4	Germany	5	4.85	54	16.46	10.80
5	Canada	2	1.94	2	0.61	1.00
6	Saudi Arabia	2	1.94	2	0.61	1.00
7	UK	2	1.94	0	0.00	0.00
8	Colombia	1	0.97	7	2.13	7.00
9	France	1	0.97	5	1.52	5.00

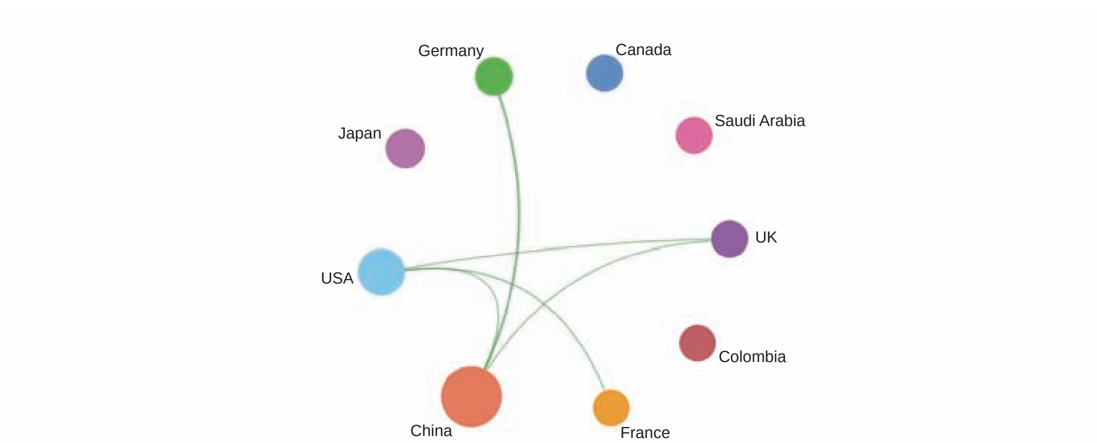

Figure 2.2.1 Collaboration network among major countries in the engineering development front of "linear and integer programming solvers"

China's solver products have experienced rapid development in recent years, achieving international recognition and serving global enterprises. With China's ongoing investment in solver research, a growing number of significant accomplishments are emerging. Domestically developed solver products are progressively approaching the technical caliber of world-class solvers and establishing a presence in the international market.

The evolution of linear and integer programming solvers unfolded in two phases: from theoretical research to solver development, optimization, and practical application. Future pivotal development trajectories encompass following two key aspects.

1) Expansion of problem scope: this entails broadening the scope of problems that can be addressed, extending beyond linear and integer programming to encompass challenges such as quadratic programming, second-order cone programming, semidefinite programming, and integer nonlinear programming.

2) Technical innovation: this involves integrating concepts from disciplines beyond mathematical optimization into the advancement of linear and integer programming solvers. This innovation aims to further heighten the solving efficiency and enlarge the array of application scenarios. Present research efforts primarily revolve around large-scale distributed computing, artificial intelligence, and quantum computing. Figure 2.2.3 illustrates its future pathway of the engineering development front of “linear and integer programming solvers”.

Table 2.2.2 Institutions with the greatest output of core patents on “linear and integer programming solvers”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of Citations/%	Citations per patent
1	International Business Machines Corporation (IBM)	16	15.53	28	8.54	1.75
2	State Grid Electronic Commerce Co., Ltd.	9	8.74	21	6.40	2.33
3	Baidu Netcom Technology Co., Ltd.	8	7.77	49	14.94	6.12
4	Guangxi Electric Power Industry Group Co., Ltd.	6	5.83	8	2.44	1.33
5	China Jiliang University	5	4.85	14	4.27	2.80
6	Fujitsu Group	5	4.85	3	0.91	0.60
7	Tsinghua University	4	3.88	19	5.79	4.75
8	Siemens AG	4	3.88	4	1.22	1.00
9	Nippon Steel Corporation	3	2.91	6	1.83	2.00
10	Shandong University	2	1.94	26	7.93	13.00

Figure 2.2.2 Collaboration network among major institutions in the engineering development front of “linear and integer programming solvers”

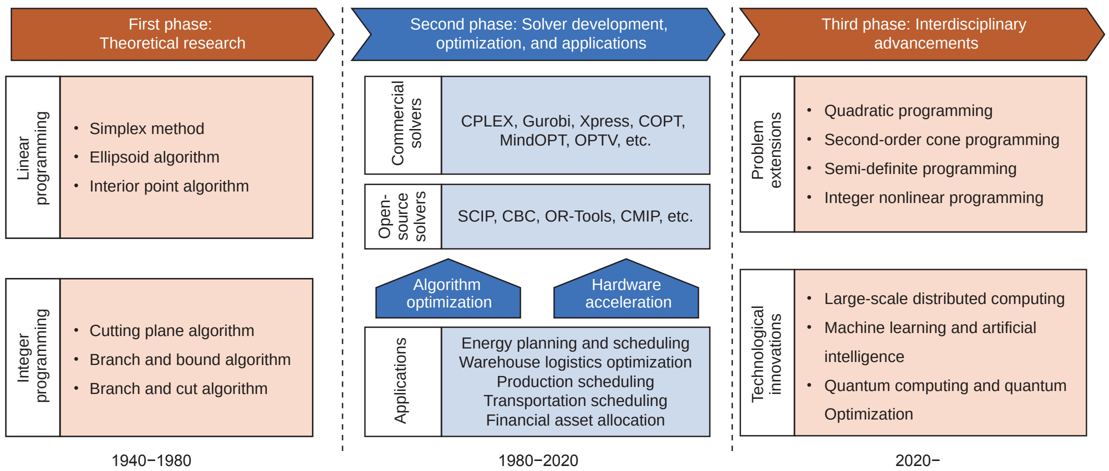

Figure 2.2.3 Roadmap of the engineering development front of “linear and integer programming solvers”

2.2.2 Intelligent factory operation and maintenance systems based on industrial internet and big data

The intelligent factory operation system, founded on industrial internet and big data, serves as a data-driven core for factory operations and maintenance management. This system gathers real-time and comprehensive data from the production process, meticulously extracts knowledge embedded within the data, and facilitates more accurate and timely monitoring and management of the operation process and production resources. Patent analysis underscores the pivotal research areas associated with this system, currently focusing on followings.

(1) Industrial big data collection and management technology

This encompasses the collection of operational data pertaining to production equipment, process flows, etc. It also involves the processing, analysis, and storage of the collected data, collectively supporting the oversight and maintenance activities of the production system. Research emphasis lies in intelligent sensor network design and deployment, assessment and optimization of data quality, and fusion processing of multisource heterogeneous data.

(2) Industrial big data-driven equipment fault diagnosis and maintenance technology

This technology diagnoses and pinpoints equipment faults through the analysis of equipment data collected via data mining, artificial intelligence, and related methods. It subsequently provides reference maintenance plans and strategies. Current areas of focus include constructing fault diagnosis models, conducting root cause analysis of faults, and managing maintenance plan information.

(3) Intelligent factory operation system based on industrial internet

Anchored in the industrial internet and incorporating big data collection, analysis, and application, this system attains intelligent operation and maintenance management for production processes and resources. It amalgamates several key enabling technologies and functional services, including data collection and management technology, equipment fault diagnosis and maintenance technology, real-time monitoring, and remote operation services. At present, technologies such as edge intelligence, cloud computing, and digital twin are evolving into essential catalysts for the system’s intelligent enhancement.

From a core patent perspective, China leads in publicly disclosed patent numbers, while the USA claims the highest average citation count (Table 2.2.3). Collaborations are observed between Italy and Israel (Figure 2.2.4). Noteworthy patent-disclosing institutions encompass ioCurrents Company and Henan Sutong Boiler Co., Ltd. (Table 2.2.4), with no established cooperative relationships among different organizations.

Looking ahead, intelligent factory maintenance systems rooted in industrial internet and big data will advance toward heightened intelligence, integration, and security. Progress in artificial intelligence will facilitate more accurate autonomous prediction of equipment failure and production risk. Simultaneously, advancements in data fusion technology will amplify system integration, propelling a sophisticated leap across the entire value chain. Furthermore, enhancements in data encryption and authentication technology will fortify the privacy protection and security management of multiparty data, establishing a robust underpinning for the system's reliability and security. Figure 2.2.5 outlines the developmental trajectory for "intelligent factory operation and maintenance systems based on industrial internet and big data".

Table 2.2.3 Countries with the greatest output of core patents on "intelligent factory operation and maintenance systems based on industrial internet and big data"

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	China	35	53.03	88	8.07	2.51
2	Republic of Korea	19	28.79	7	0.64	0.37
3	USA	11	16.67	976	89.54	88.73
4	Israel	1	1.52	19	1.74	19.00
5	Italy	1	1.52	19	1.74	19.00

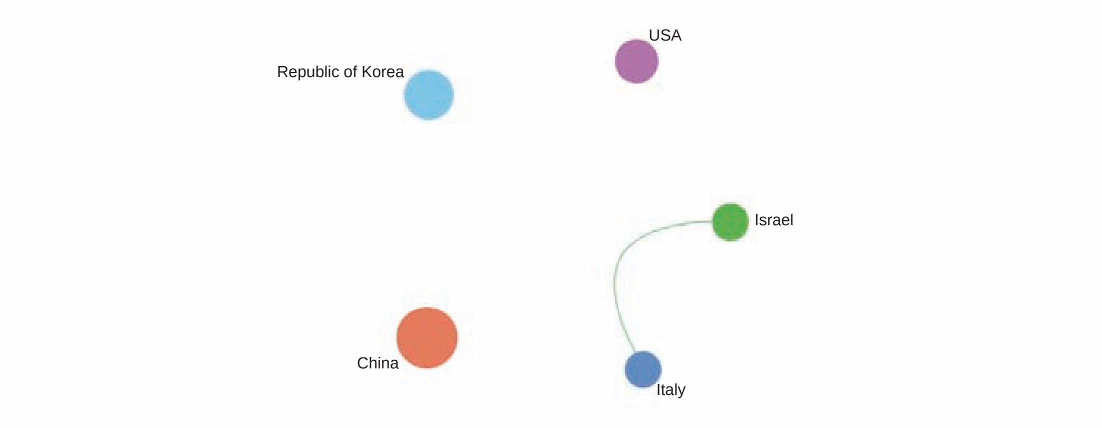

Figure 2.2.4 Collaboration network among major countries in the engineering development front of "intelligent factory operation and maintenance systems based on industrial internet and big data"

Table 2.2.4 Institutions with the greatest output of core patents on "intelligent factory operation and maintenance systems based on industrial internet and big data"

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of Citations/%	Citations per patent
1	ioCurrents Corporation	6	9.09	720	66.06	120.00
2	Henan Sito Boiler Co., Ltd.	5	7.58	4	0.37	0.80
3	AiKEN Technology Co., Ltd.	4	6.06	32	2.94	8.00
4	Tsinghua University	4	6.06	9	0.83	2.25
5	DLIT Co., Ltd.	4	6.06	0	0.00	0.00
6	Korea Electronics Technology Institute	3	4.55	5	0.46	1.67
7	Wistron Technology	3	4.55	3	0.28	1.00
8	SFIP Corporation	2	3.03	237	21.74	118.50
9	Mobileye Vision Technologies Ltd.	2	3.03	38	3.49	19.00
10	Guangzhou Bote Intelligent Information Technology Co., Ltd.	2	3.03	18	1.65	9.00

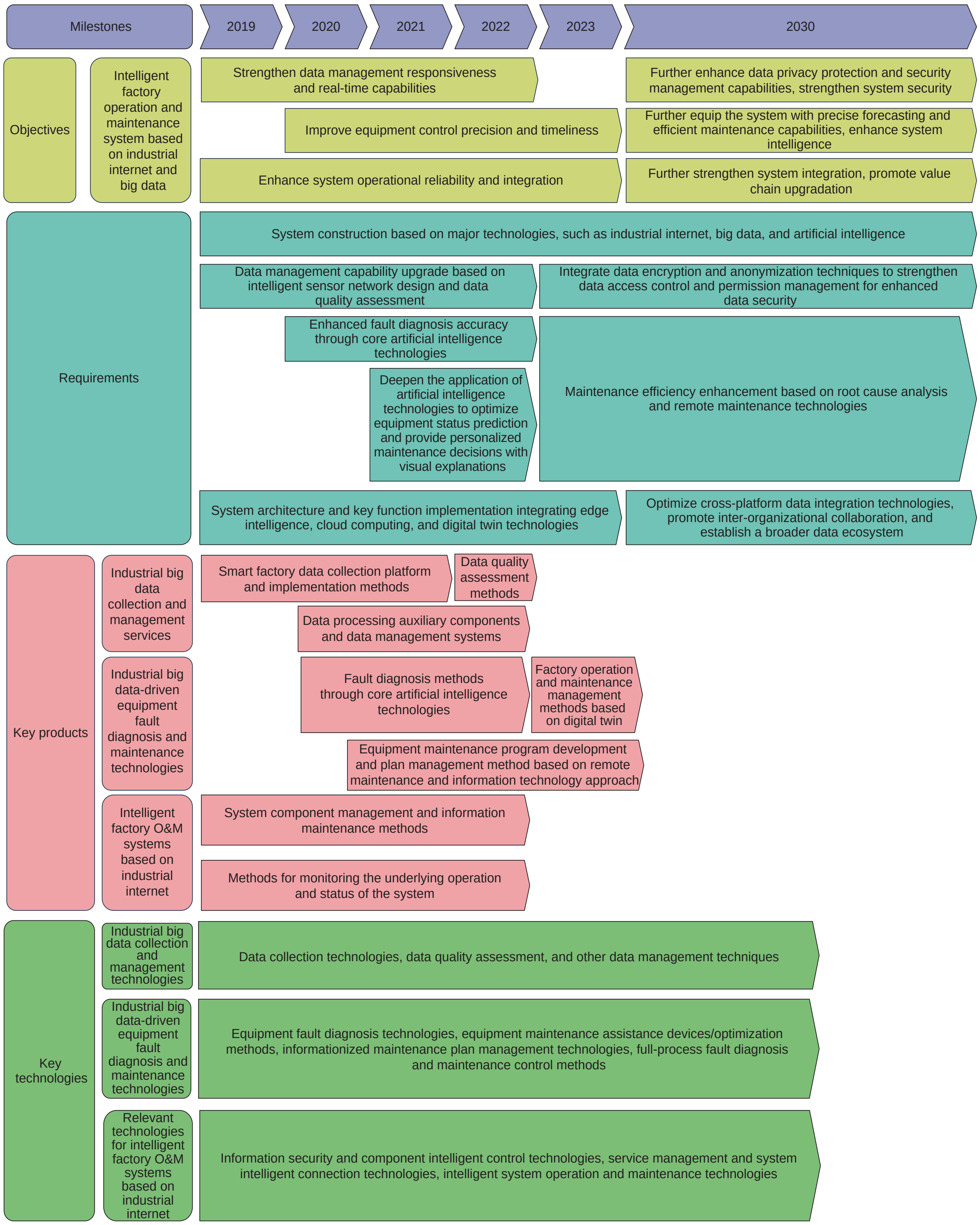

Figure 2.2.5 Roadmap of the engineering development front of “intelligent factory operation and maintenance systems based on industrial internet and big data”

2.2.3 Methods and systems for automatic building design generation based on deep learning

The primary goal of deep learning-based automatic building scheme generation is to leverage deep learning technology for the automated creation of architectural design plans. Its essence lies in extracting and learning the intrinsic rules of architectural design from existing materials, thereby fulfilling project requirements automatically. These methods and systems have the potential to enhance designers' productivity by freeing them to focus on higher-level creativity and significant decision-making. This can reduce uncertainties related to design quality and cost in traditional design models while further elevating the digitalization, automation, and intelligence levels of architectural design.

As the technological bedrock of this domain, deep learning models have played an indispensable supporting role in the advancement of key research directions. For example, the fully convolutional neural network, introduced in 2014 for image and semantic segmentation, has found wide-ranging application in the automatic semanticization of architectural schemes. In the same year, two deep generative models, variational autoencoders and generative adversarial networks, emerged as pivotal engines for image generation and style transfer. Nonetheless, these studies have predominantly centered on low- to high-rise buildings, with limited attention given to spatial structure and superhigh-rise constructions. In 2017, graph convolutional networks were introduced to solve spatial arrangement challenges in generating beams, columns, walls, and more. The transformer model, also introduced in 2017, has been used for automated compliance checking, ensuring the generated scheme's adherence, safety, and quality. However, it has not yet effectively addressed the recognition and processing of ambiguous design clauses.

By focusing on the creation of secure, efficient, and stable design systems via an array of automatic generation methods, the provision of high-quality customized services to designers becomes feasible. While automatic generation methods themselves face numerous challenges in terms of feasibility and reliability, the research and development of associated systems are still in their nascent stages. Apart from automatic generation methods, existing automatic generation systems often lack the integration of critical functional modules, including automatic compliance checks, interactive scheme modification, scheme evaluation, multiperson collaboration, user privacy protection, file encryption, model rendering, and intelligent optimization.

In the engineering development front of "methods and systems for automatic building design generation based on deep learning", the overall status of core patents is shown in Tables 2.2.5 and 2.2.6. Specifically, the top three countries in terms of the number of core patents are the USA, Republic of Korea, and China. The primary institutions responsible for the output of core patents include Azova Inc. in the USA, SureSoft Technologies Inc. in Republic of Korea, and International Business Machines Corporation (IBM), among others. At the national level, there is currently limited collaboration among countries. At the institutional level, however, there exists a collaborative relationship between ChangSoft I&I in Republic of Korea and Yonsei University (Figure 2.2.6). The absence of extensive international collaboration may be attributed to regulatory measures concerning artificial intelligence technologies and divergent research orientations among institutions.

To elevate the feasibility, reliability, and diversity of autonomously generated architectural proposals, Figure 2.2.7 articulates the avant-garde trajectory of this scholarly endeavor. By extensively employing next-generation digital interaction technologies coupled with deep generative models, the investigation seeks to amplify and refine collaborative human–machine design methodologies, thereby harmonizing the prescriptive and inventive dimensions of design frameworks. Grounded in ontological paradigms, the research explores strategic amalgamations of multi-disciplinary analytical engines with design conventions, culminating in the conception of congruent systems for the self-generating architecture blueprints. To address the challenges posed by data-deficient complex architectures, supplementary analyses are executed through the medium of parametric modeling and cloud-based computational techniques, thereby facilitating data augmentation. Furthermore, the study categorizes the latent ambiguities present within design stipulations, advances methodologies for their identification and rectification, and coherently integrates these elements into extant frameworks for automated compliance verification.

Table 2.2.5 Countries with the greatest output of core patents on “methods and systems for automatic building design generation based on deep learning”

No.	Country	Published patents	Percentage of published patents/%	Citations	Percentage of Citations/%	Citations per patent
1	USA	15	57.69	206	99.04	13.73
2	Republic of Korea	9	34.62	2	0.96	0.22
3	China	1	3.85	0	0.00	0.00
4	Japan	1	3.85	0	0.00	0.00

Table 2.2.6 Institutions with the greatest output of core patents on “methods and systems for automatic building design generation gased on deep learning”

No.	Institution	Published patents	Percentage of published patents/%	Citations	Percentage of citations/%	Citations per patent
1	Azova Inc.	4	15.38	12	5.77	3.00
2	SureSoft Technologies Inc.	4	15.38	0	0.00	0.00
3	International Business Machines Corporation (IBM)	3	11.54	15	7.21	5.00
4	Google Inc.	2	7.69	86	41.35	43.00
5	TIBCO Software Inc.	2	7.69	38	18.27	19.00
6	Nuance Communications Inc.	1	3.85	50	24.04	50.00
7	Advanced Micro Devices, Inc.	1	3.85	5	2.40	5.00
8	ChangSoft I&I Co., Ltd.	1	3.85	1	0.48	1.00
9	Samsung Electronics Co., Ltd.	1	3.85	1	0.48	1.00
10	Yonsei University	1	3.85	1	0.48	1.00

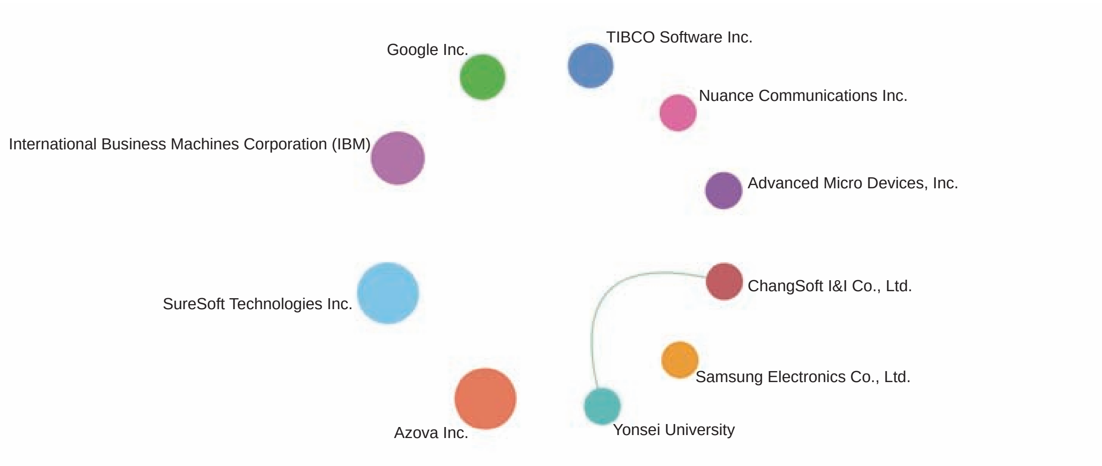

Figure 2.2.6 Collaboration network among major institutions in the engineering development front of “methods and systems for automatic building design generation based on deep learning”

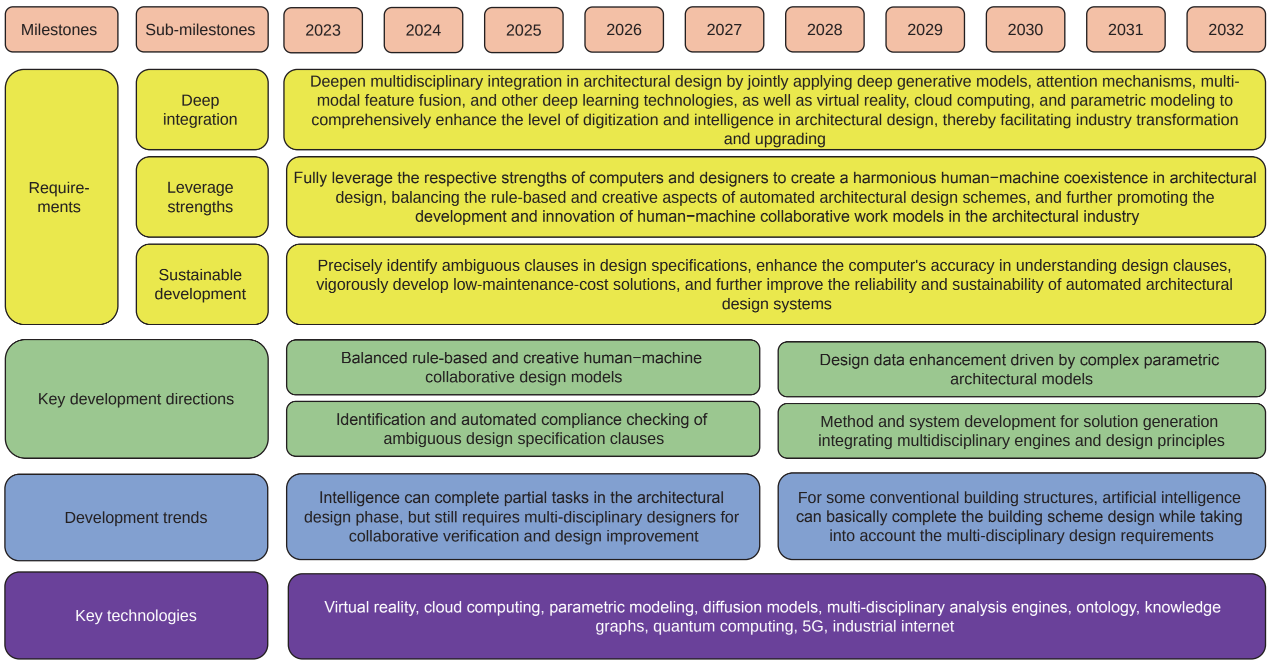

Figure 2.2.7 Roadmap of the engineering development front of “methods and systems for automatic building design generation based on deep learning”

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