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## Research on Nanotechnology Development Strategies of Major Science and Technology Powers Worldwide and Their Implications (Post-print)

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### Abstract

Through an analysis of nearly 160 strategic planning documents for guiding nanotechnology development released by the world's major science and technology powers (regions) during 2000–2023, it is found that these countries (regions) have implemented a series of strategic initiatives with common characteristics that have successfully promoted nanotechnology development, primarily including: attaching great importance to nanotechnology; establishing inter-departmental management institutions; formulating strategic plans and implementing major research programs; establishing multidisciplinary research centers; investing in research infrastructure construction; promoting integration and development with other scientific and technological fields; facilitating the industrialization of research outcomes; paying special attention to environmental and health impacts; actively cultivating and recruiting talent; and vigorously conducting international cooperation. In recent years, these countries (regions) have continued to attach great importance to nanotechnology development. Based on an analysis of the current state of China's nanotechnology development, this paper recommends that China establish a national nanomaterials data center and a nanotechnology think tank, and construct a talent cultivation system that aligns with global science and technology development trends and the demands of nanotechnology development.

## Full Text

### Study on R&D Strategies in Nanoscale Science and Technology of Global Powerhouses and Insights

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## Abstract

By analyzing nearly 160 strategic planning documents guiding nanoscale science and technology development released by major global scientific and technological powers (regions) from 2000 to 2023, this study identifies a series of common strategic measures that have successfully promoted nanotechnology advancement. These include: attaching great importance to nanotechnology; establishing cross-departmental management institutions; formulating strategic plans and implementing major research programs; building multidisciplinary research centers; investing in research infrastructure; promoting integration with other technologies; facilitating industrialization of research outcomes; paying special attention to environmental and health impacts; actively cultivating and recruiting talent; and vigorously pursuing international cooperation. In recent years, these countries and regions have continued to maintain high-level attention to nanotechnology development. Based on an analysis of China's current nanotechnology development status, this paper recommends that China establish a national nanomaterials data center and a nanotechnology think tank, and build a talent cultivation system adapted to global scientific and technological trends and the development needs of nanotechnology.

**Keywords:** nanoscale science and technology, strategic planning, strategy study, intelligence

## 1.1 Development Experience

A review of strategic planning documents for nanotechnology development from 2000 to 2023 reveals that despite significant differences in political systems and economic levels, major scientific and technological powers have adopted ten common strategic measures.

First, they regard nanotechnology as a critical technology for economic devel-

opment and national competitiveness. The U.S. National Security Strategy lists nanotechnology among key emerging technologies vital to economic growth and security. The European Union identifies nanotechnology as one of six key enabling technologies that will keep Europe globally competitive in high-value-added, technology-intensive products and services. The UK believes that developing advanced materials and nanotechnology can drive economic growth, create jobs, achieve industrial transformation and upgrading, and maintain its position as a world-leading nation. Russia's National Security Strategy prioritizes strategic high-tech including nanotechnology, incorporating it into its Priority Directions for Science, Technology and Engineering and Critical Technology List. Japan positions "nanotechnology and materials" as core technologies for creating new value and foundational technologies supporting a super-smart society. China's State Council has organized special lectures on the current status and development trends of nanotechnology.

Second, recognizing the interdisciplinary and cross-cutting nature of nanotechnology, these countries have established inter-agency and cross-sector development organizations. The U.S. established the Nanoscale Science, Engineering, and Technology subcommittee under the National Science and Technology Council, comprising representatives from the White House Office of Science and Technology Policy, Office of Management and Budget, and participating agencies of the National Nanotechnology Initiative, responsible for coordinating national nanotechnology planning, budgeting, implementation, and evaluation. The UK created a Ministerial Group on Nanotechnology to coordinate relevant government departments and strengthen leadership on nanotechnology work. Russia established a permanent Government Commission on Nanotechnology to ensure close ties between federal executive authorities and the business and scientific communities. Japan formed the Nanotechnology and Materials Science Committee, with members primarily from universities, research institutions, and enterprises, tasked with analyzing international development trends and Japan's status in nanotechnology and materials, and reviewing development plans. China established the National Steering and Coordinating Committee for Nanoscience and Technology, composed of representatives from the Ministry of Science and Technology, National Development and Reform Commission, Ministry of Education, Ministry of Finance, Chinese Academy of Sciences, Chinese Academy of Engineering, National Natural Science Foundation, and expert groups, responsible for guiding and coordinating national nanoscience and technology work.

Third, countries have formulated dedicated nanotechnology development strategies, deployed major research programs, and invested substantial funding. The U.S. has developed and regularly updated strategic plans for its National Nanotechnology Initiative, deploying major programs such as the "Nanotechnology Signature Initiative" and "Nanotechnology-Inspired Grand Challenge." From fiscal years 2001 to 2021, the U.S. federal government invested over \$31 billion in the National Nanotechnology Initiative. The EU formulated the Action Plan for Nanoscience and Nanotechnology 2005–2009; under the Horizon 2020 program (2014–2020), it budgeted nearly €1.7 billion for nanotechnology-related research

under the “Nanotechnology, Advanced Materials, Advanced Manufacturing and Processing, and Biotechnology” theme, and launched the “Graphene Flagship” major project with planned investment of €500 million. The UK developed the UK Nanotechnologies Strategy: Small Technologies, Great Opportunities, deploying 43 actions across four areas: business, industry and innovation; environmental, health and safety research; regulation; and stakeholders. France launched the “Nano 2022” major program in March 2019, with the government planning to invest €1 billion to support R&D and pre-industrialization of next-generation electronic components. Germany formulated the Nano Action Plan 2010, Nanotechnology Action Plan 2015, and Nanotechnology Action Plan 2020. In recent years, German federal and state governments have provided over €600 million annually for nanotechnology funding. Russia approved the Nanotechnology Industry Development Strategy in April 2007, under which it established Rusnano and approved the Nanotechnology Industry Development Program through 2015, planned to be financed at approximately 317.9 billion rubles. Japan formulated the Nanotechnology and Materials Science and Technology R&D Strategy, with the Ministry of Education, Culture, Sports, Science and Technology and the Ministry of Economy, Trade and Industry deploying major programs such as the “Integrated Materials Development Program” and “Ultra-Advanced Materials Ultra-High-Speed R&D Infrastructure Technology Program.” South Korea formulated the Nanotechnology Comprehensive Development Plan and National Nanotechnology Roadmap, updated regularly; from 2001 to 2020, it invested 7.9 trillion won in nanotechnology R&D. China formulated the National Nanoscience and Technology Development Outline (2001–2010) and, under the National Medium- and Long-Term Program for Science and Technology Development (2006–2020), deployed major programs including the National Basic Research Program on Nanotechnology and the National Key R&D Program on Nanotechnology.

Fourth, countries have established multidisciplinary nanotechnology research centers leveraging the strengths of universities, research institutions, and enterprises. The U.S. National Science Foundation established 19 Nanoscale Science and Engineering Centers, each led by one university with participation from several universities or enterprises. The UK invested in graphene research institutions at the University of Manchester, including the National Graphene Institute, Graphene Engineering Innovation Centre, and Henry Royce Institute. The Fraunhofer Society for the Advancement of Applied Research in Germany operates 76 research units, with 14 institutes including the Institute for Applied Polymer Research forming a nanotechnology business alliance. Russia designated the Kurchatov Institute as the national lead unit for nanoscience and technology research, one of Russia’s first national research centers. Since 2007, Japan has implemented the World Premier International Research Center Initiative, establishing 13 centers by the end of 2020, with at least seven such as the International Center for Materials Nanoarchitectonics and the Institute for Nano Life Science Research engaged in nanotechnology research. China has established high-level research institutions including the National Center for

Nanoscience and Technology and the National Engineering Research Center for Nanotechnology and Application.

Fifth, countries have invested in public nanotechnology research infrastructure platforms, including instrument platforms, major research facilities, and digital platforms. For over 40 years, the U.S. NSF has invested in the National Nanotechnology Coordinated Infrastructure and the Nanotechnology Computational Network. The former comprises nanotechnology research facilities at 16 universities, while the latter provides over 500 nanoscale computational and simulation tools to researchers worldwide. The EU's Horizon 2020 program funded the European Nanoscience Foundry and Fine Analysis platform, composed of research facilities in 10 countries including Italy, France, and Germany, providing one-stop services for users. Since 2002, Japan has invested in shared nanotechnology research facility platforms; the third phase (2012–2021) constructed an advanced instrumentation network of 25 institutions centered on the National Institute for Materials Science, and established a materials data platform at the institute to support data-driven materials R&D. China's National Science and Technology Infrastructure Platform Center has built a national network management platform for major research infrastructure and large-scale scientific instruments; the Nanovac Interconnected Experimental Station Phase II construction project was successfully completed in February 2023. The Chinese Academy of Sciences established the Beijing Regional Center for Materials Science and Nanotechnology Large-scale Instruments, leveraging member institutions' research and equipment advantages to provide open and shared services to hundreds of units nationwide.

Sixth, countries have promoted the convergence of nanotechnology, biotechnology, information technology, and cognitive science. The U.S. established the “Nanotechnology-Inspired Grand Challenge: Future Computing” program to revolutionarily enhance computing capabilities through the integration of nanotechnology, computer science, and neuroscience. Russia includes nano-bio-info-cognitive convergence technology in its Critical Technology List, and the Kurchatov Institute established a Nano-Bio-Info-Cognitive-Socio Convergence Natural Technology Center. Japan has made convergence a development direction for its nanotechnology, achieving new functions and creating new materials through integration with cutting-edge technologies in other fields. South Korea launched the “Nano Convergence 2020” program in 2012, planning to invest 513 billion won by 2020 to prioritize support for four strategic projects: next-generation semiconductors, nanoscale elastic components, efficient energy conversion technology, and water environment and resource treatment technology.

Seventh, countries have established manufacturing research bases to accelerate the commercialization of nanotechnology research results. The U.S. established the National Nanomanufacturing Network to accelerate the transition of nanotechnology from laboratory breakthroughs to mature commercial advanced manufacturing technologies. The UK promotes nanotechnology application in manufacturing through industry-university-research cooperation platforms such

as the Manufacturing Technology Centre, Future Manufacturing Research Hubs, and High Value Manufacturing Catapult. France established a leading European micro-nanotechnology innovation park in the Grenoble technology cluster. France, Norway, the Netherlands, and other countries formed the distributed nanomanufacturing research infrastructure “European Nanotechnology Laboratory” to improve the quality and efficiency of European nanomanufacturing. Rusnano established 15 nanotechnology centers across Russia (as of October 2019) to concentrate equipment and technological advantages and provide incubation services for small and micro enterprises, promoting the commercialization of nanotechnology research results. South Korea established six nanomanufacturing centers in Daejeon, Suwon, Pohang, Gwangju, Jeonju, and Daegu as industrial technology development platforms. China has established multiple high-level industrialization bases including the Beijing Nanotechnology Industry Park and Suzhou Nanotech City. In November 2022, the National Graphene Innovation Center was approved, becoming one of 26 national-level manufacturing innovation centers.

Eighth, countries attach great importance to the potential impacts of nanotechnology on human health and the natural environment. The U.S. National Nanotechnology Initiative lists “supporting the responsible development of nanotechnology” as one of its four major goals and has formulated a nanotechnology environmental, health, and safety research strategy, investing over \$1.26 billion in such research from 2005 to 2020. In June 2013, the EU released EU Nanosafety (2015–2025): Towards Safe and Sustainable Nanomaterials and Nanotechnology Innovations, outlining priority areas and development roadmaps for EU nanosafety research. The UK Royal Society and Royal Academy of Engineering jointly published the report Nanoscience and Nanotechnologies: Opportunities and Uncertainties in July 2004, focusing on nanosafety issues. The German federal government consistently prioritizes nanosafety, allocating 10% of nanotechnology research funding to risk research and corresponding preventive measures. Russia is highly concerned about threats posed by nanotechnology to human life and global development, particularly regarding military security impacts. Japan has deployed a series of research projects on the toxicity and exposure risks of nanomaterials, focusing on nanoscale titanium dioxide, carbon black, silver, carbon nanotubes, and fullerenes. South Korea formulated the Comprehensive Plan for Nanosafety Management to address nanotechnology impacts on human health and the environment, and has forward-deployed nanosafety research through its National Nanotechnology Roadmap. Chinese scientists proposed research plans and safety issues for nano-bio-environmental effects as early as 2001, with the Xiangshan Science Conference repeatedly addressing nanosafety as a theme. China’s National Basic Research Program, National Key Basic Research Program on Nanotechnology, and National Key R&D Program on Nanotechnology have all deployed multiple nanotechnology safety research projects.

Ninth, countries actively cultivate and recruit professional talent while promoting public understanding of nanotechnology through various science populariza-

tion activities. In talent cultivation, the University at Albany, State University of New York established the College of Nanoscale Science and Engineering in 2004, the first nanotechnology college in the U.S. The UK established doctoral training centers in nanotechnology at universities to train PhD students. South Korea had 38,087 nanotechnology students in 2019, with an average annual growth rate of approximately 3.7%. In 2010, Soochow University, in collaboration with Suzhou Industrial Park and the University of Waterloo in Canada, established China's first Nano Science and Technology College, representing the first attempt to establish interdisciplinary nanoscience education in China. In September 2022, the Academic Degrees Committee of the State Council and the Ministry of Education issued the Graduate Education Discipline and Specialty Catalogue (2022), adding the first-level interdisciplinary discipline "Nanoscience and Engineering." In talent recruitment, Russia attracts renowned foreign scientists and Russian-origin scientists to conduct collaborative research in Russia. Japan's World Premier International Research Centers provide world-class research and living environments for foreign researchers, with English as the first working language. China also attracts outstanding overseas talent through various talent programs. In science popularization, countries actively rely on universities, research institutions, museums, and even amusement parks (such as Disneyland) to bring the public in for education through various themed activities (such as the U.S. "Nano Day" events). They also produce lively popular science materials such as animations and videos for public dissemination via the internet, particularly using mobile publicity facilities (such as the U.S. NanoExpress and Germany's NanoTruck) to reach out to the public, especially youth.

Tenth, countries actively engage in international cooperation. They have conducted targeted and fruitful nanoscience and technology cooperation under bilateral, multilateral, and international organization frameworks (e.g., OECD, APEC, BRICS, ISO). Nanotechnology safety is a key cooperation priority. The EU and the U.S. have cooperated in nanosafety since 2011, jointly publishing the EU-US Nanoinformatics Research Roadmap 2030 in 2018. The EU has also established cooperative relationships in nanosafety with Mexico, Brazil, South Korea, South Africa, and the Asian Nano Forum. In October 2008, the first U.S.-China Nano-Bio and Nano-Medicine Symposium was held in Beijing, with cooperative research on nanomaterial safety issues among the discussion topics. It must be noted that while cooperating under international organization frameworks, countries are also using these frameworks to protect their own interests. For example, regarding nanotechnology standards, countries are competing for dominance in standard-setting within the ISO Nanotechnology Committee and IEC Nanoelectronics and System Technology Committee to secure advantages for their nanotechnology products in international markets.

## 1.2 Latest Trends

After decades of rapid development, nanotechnology has evolved from an emerging technology to an enabling technology that advances alongside developments in various application fields. In this context, compared with the early 21st century, the number of nanotechnology development strategies released by countries has decreased in recent years, with R&D funding shifting more toward specific application fields. Whether it remains necessary to maintain strategic emphasis and special funding for nanotechnology has become an important question. Through investigation of recent (2020–2023) planning and deployment by major global scientific and technological powers, this paper draws three conclusions.

First, countries continue to maintain high-level attention to nanotechnology. In October 2020, the U.S. released the National Nanotechnology Initiative 2021 budget report, stating that continued investment in nanotechnology is an important foundation for establishing future industries and maintaining leadership in semiconductors and strategic computing, and that the U.S. must continue to maintain global leadership in nanotechnology. In April 2022, the White House Office of Science and Technology Policy again stated in a report to Congress that nanotechnology is an important component of future industries. In September 2021, the French Prime Minister listed nanoelectronics alongside quantum mechanics, artificial intelligence, green hydrogen, batteries, green biotechnology, and health as strategic areas requiring key investment in a speech at the National Industry Council. In September 2021, South Korea's Ministry of Science and ICT released the 5th Nanotechnology Comprehensive Development Plan, which allocated 5.6 trillion won for nanotechnology R&D from 2021 to 2025, demonstrating high-level attention and active development of nanotechnology. The Chinese Academy of Sciences and the National Natural Science Foundation jointly authored the *China Nanoscience 2035 Development Strategy*, which states that nanotechnology, with its interdisciplinary, foundational, leading, and transformative characteristics, has become a new engine driving scientific development, with its disruptive and transformative features for industry highlighted as an important source of future transformative technologies and industrial upgrading.

Second, countries emphasize addressing major societal challenges. In October 2021, the U.S. released a new strategic plan for the National Nanotechnology Initiative, establishing the “National Nanotechnology Challenges” program to mobilize the nanotechnology community and other research forces to cooperate in addressing major global challenges. The first program, Nano4EARTH, aims to address global climate change and was launched in January 2023. In July 2022, Japan's 11th Nanotechnology and Materials Science Committee held its 6th meeting to discuss the draft R&D Plan for Nanotechnology and Materials Science and Technology, proposing that Japan's goal in developing nanotechnology is to promote economic growth and innovation and ultimately realize a super-smart society. South Korea's 5th Nanotechnology Comprehensive De-

velopment Plan lists four strategic objectives, with Objective 1 “Strengthen creative or challenging and globally leading nanotechnology research” stating that nanotechnology should provide solutions to major social and economic problems. China’s National Key R&D Program “Nanofrontiers” deployed 27 projects in 2021, with approximately two-thirds related to major national needs such as integrated circuits, disease diagnosis and treatment, renewable energy, and water pollution control. The National Natural Science Foundation’s 14th Five-Year Development Plan proposes focusing on key scientific questions in nanoscience and technology for national strategic needs in high-performance electronics, optoelectronics, quantum and spin solid-state devices, developing high-precision nanofabrication methods, and breaking through key core technologies constraining China’s nanotechnology field. By 2025, China aims to achieve ordered integration of high-performance nanodevices, catalyzing nanotechnology transformation and emerging industries.

Third, countries are actively responding to the shift toward a data-intensive R&D paradigm. The U.S. 5th strategic plan includes Objective 3 “Provide infrastructure for sustainable support of nanotechnology research, development, and utilization,” which newly adds “improve database interoperability” to provide large datasets for AI development. In 2021, Japan’s Ministry of Education, Culture, Sports, Science and Technology deployed two major programs through 2030: “Materials R&D Based on Data Generation and Utilization” and “Advanced Research Infrastructure for Materials,” aiming to sustainably and efficiently generate, accumulate, and utilize materials R&D data based on Japan’s supercomputers, research infrastructure, advanced instrumentation networks, and research databases, thereby creating new functional materials and achieving digital transformation of research. South Korea’s 5th Nanotechnology Comprehensive Development Plan proposes establishing and expanding nanotechnology and materials data platforms under Objective 1. South Korea is building the Korea Materials Data Station, with planned investment of 19.6 billion won in 2022. In June 2020, China’s Ministry of Science and Technology launched the national key R&D program scientific data collection, with data generated by the “Nanotechnology” special program uploaded to the National Basic Science Data Center.

## 2 China’s Nanotechnology Development Status

China’s nanotechnology research began almost simultaneously with the rest of the world. After nearly 40 years of development, it has achieved remarkable accomplishments, ranking first globally in annual nanotechnology paper publications, highly cited papers, and patent applications, becoming an important contributor to global nanotechnology progress and a major player in nanotechnology frontier R&D. Specifically, China has achieved international leadership in some basic research directions. Chinese scientists pioneered the discovery of aggregation-induced emission, proposed important scientific concepts such as single-atom catalysis and nanozymes, and developed world-leading

nanomaterial systems including aggregation-induced emission materials, single-atom catalysts, nanozymes, porous materials, two-dimensional materials, rare-earth functional materials, and organic optoelectronic materials. Three research achievements—“Aggregation-Induced Emission,” “Nanoconfined Catalysis,” and “Creation and Application of Ordered Mesoporous Polymer and Carbon Materials”—won the National Natural Science Award First Prize, while research on “Controlled Catalytic Synthesis of Single-Walled Carbon Nanotubes,” “Novel Nanodrug Delivery Systems to Overcome Tumor Chemotherapy Resistance,” and “Fundamental Research on Ultrafast Laser Micro-Nano Fabrication of Special Optoelectronic Devices” received the National Natural Science Award Second Prize.

China’s efforts in applied research and technology transfer have also begun to bear fruit. Complete production technologies represented by methanol-to-olefin catalysts have achieved large-scale industrialization. Electronic tickets printed using nano-green printing technology have been successfully used for the National Science and Technology Week, Beijing APEC meetings, and subway cards. Nanotechnology achievements have played a solid role in fighting COVID-19, developing aerospace, and maintaining national defense security. China also boasts a group of internationally influential leading talents in nanotechnology, who have received international awards such as the UNESCO Medal for Contributions to Nanoscience and Nanotechnology Development, and have attracted world-renowned nanotechnology experts including Akira Fujishima from Japan and Michael Grätzel from Switzerland to collaborate in China through superior research conditions. In summary, China’s nanotechnology research has entered the ranks of world leaders, with the U.S. National Academy of Sciences acknowledging in an evaluation report that China’s active and effective R&D strategy is likely to place it in a leading position in this crucial technological field.

However, it must be noted that China only stands alongside the U.S. in basic nanotechnology research; there remains a gap in industrialization compared with the U.S. and Japan. Chinese universities and research institutions severely underinvest in R&D for translating research results from laboratory to industrial application. The effective connection mechanism between basic research and national needs or economic development remains weak, preventing many research results with good industrial prospects and application potential from being effectively transferred to domestic enterprises. China is also relatively weak in nanosafety research related to industrial development and human health, and does not pay sufficient attention to the ethics and social impacts of nanotechnology. Moreover, even in basic research, influenced by the research evaluation system, many researchers blindly follow research hotspots in pursuit of publication quantity and impact factors, paying insufficient attention to major national needs, which not only wastes substantial basic research resources but also results in excessive follow-up research, research homogenization, insufficient original innovation, and inadequate capacity for directional leadership. Of course, these problems are not unique to nanotechnology in China but are common across scientific and technological fields.

### 3 Policy Recommendations

The *China Nanoscience 2035 Development Strategy* proposes that by 2035, China's overall innovation capacity in nanoscience basic research should reach world-leading levels, achieving breakthroughs in fundamental principles of nanosystems, developing nanodevices and nanomaterials with independent intellectual property rights, establishing new methods for nanobiosafety evaluation, and promoting nanotechnology applications in energy, environment, information, medicine, and health. Based on this vision, combined with international development experience, latest global trends, and China's nanotechnology development status, this paper proposes four recommendations.

First, focus on the “Four Orientations” with emphasis on technology transfer. R&D deployment should face world science and technology frontiers, the main economic battlefield, major national needs, and people's health, guiding nanotechnology researchers to tackle major global frontier scientific issues and prominent problems in China's economic and social development, especially “bottleneck” issues, striving to achieve high-level scientific and technological self-reliance. For basic nanotechnology research with technology transfer prospects, we recommend using national strategic needs as guidance, developing technology roadmaps, promoting technology transfer through government-industry-university-research cooperation, scientifically planning industrial spatial layout, and advancing differentiated, specialized, and clustered development to avoid low-level redundant construction and vicious competition.

Second, adapt to the data-intensive R&D paradigm by building a national nanomaterials data center. In the era of data-intensive R&D, the world's scientific center will inevitably be a scientific data center. We recommend coordinated deployment of nanomaterials database construction, led by several institutions with data advantages, using a collaborative model among universities, research institutions, and enterprises, with distributed layout, first demonstrating then scaling up, and developing into a national scientific data center through long-term cultivation. The database should include not only data on nanomaterial synthesis methods, material structures and properties, and various characterization results, but also algorithm development platforms. Data format standards should be established to ensure interoperability among databases and connectivity with chemical regulatory agency databases, with formats convenient for machine learning and supercomputer processing. A data verification mechanism should be established to eliminate false data and maintain research integrity.

Third, establish nanotechnology think tanks to strengthen strategic planning top-level design. We recommend drawing on the successful experience of foreign nanotechnology think tanks such as South Korea's National Nanotechnology Policy Center and Germany's Fraunhofer Institute for Systems and Innovation Research to build professional think tank institutions or teams dedicated to nanotechnology development strategy research, making China's nanotechnology strategic planning and development layout more scientific and reflective

of national needs. Think tanks should be responsible for intelligence collection, situation analysis, technology foresight, level assessment, and technology evaluation; assist strategic scientists in identifying nanotechnology frontier research directions that may generate major innovative research achievements or profoundly influence future S&T development trajectories, and formulate development plans and technology roadmaps.

Fourth, seize the opportunity of the new first-level discipline to establish a talent cultivation system adapted to S&T development trends and nanotechnology development needs. During school training, we recommend offering artificial intelligence and data analysis courses to adapt to the data-intensive R&D paradigm, establishing major research infrastructure internship programs to adapt to the trend that major breakthroughs increasingly depend on large scientific facilities and cultivate collaborative spirit around such facilities, offering environmental protection and research ethics courses to cultivate awareness of responsible nanotechnology development, and offering writing and communication courses to enhance students' ability to communicate and popularize nanotechnology to all sectors of society. We should attach importance to cultivating young people under 35 at the early career stage (from PhD graduation to associate researcher), providing them with policy guarantees to devote themselves fully to research. Riding the wave of the "break the five-only" reform, we should establish talent and S&T evaluation mechanisms that encourage researchers to engage in technology transfer.

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*Note: Figure translations are in progress. See original paper for figures.*

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