# Domestic and International Open Science: Practical Progress and Future Exploration (Postprint)

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## Abstract

[Purpose/Significance] Timely tracking and analysis of developments in domestic and international open science practices can provide decision-making support for science and technology management departments to adjust open science policies and plan open science directions. [Method/Process] Current open science research and practice are summarized across four dimensions: the conceptual connotation and practical significance of open science, progress in international open science practices, progress in domestic open science practices, and future development trends of open science. [Results/Conclusion] Open science represents an inevitable evolution from closed knowledge to innovation; the international community has established sound practices in open science strategies, open infrastructure, open scientific data, and open-access journals; China still requires enhancement in institutional planning, culture cultivation, degree of openness, and brand reputation regarding open science; going forward, open science will develop toward globalization, FAIRification, ecologicalization, and cloudification.

## Full Text

### The Practice Progress and Future Exploration of Open Science at Home and Abroad

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**Abstract:** *[Purpose/Significance]* Timely tracking and analyzing the practical progress of open science both domestically and internationally can provide decision-making support for science and technology management departments to adjust open science policies and plan open science directions. *[Method/Process]* This paper summarizes current research and practice in open science across four dimensions: the conceptual connotation and practical significance of open science, international open science practice progress, domestic open science practice progress, and future development trends of open science. *[Results/Conclusions]* Open science represents the inevitable evolution of knowledge from seclusion to innovation. The international community has implemented sound practices in open science strategies, open infrastructure, open scientific data, and open access journals. China still needs improvement in institutional planning, cultural cultivation, degree of openness, and brand reputation. In the future, open science will develop toward globalization, FAIRification, ecologicalization, and cloudification.

**Keywords:** open science; scientific community; Global Open Science Cloud; FAIR principles; open ecology

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## Introduction

In the wave of globalization, the formulation of sustainable and innovative solutions requires effective, transparent, and dynamic scientific research outcomes as support. However, the production of research results depends not only on academia but also on the joint efforts of the entire society. To ensure that scientific achievements truly benefit all humanity and that no one is left behind in enjoying the dividends of science, we must transform the current scientific research production process and result dissemination pathways. Open science has become an inevitable choice for scientific development in the context of research paradigm transformation [?]. The concept of open science has gained universal consensus within the scientific community [?]: European Commission Vice President N. Kroes once stated that "to make progress in science, we need to open up and share" [?]; UNESCO convened a meeting of science and technology representatives from multiple countries, calling for "promoting open science and strengthening cooperation" to combat COVID-19 [?]; Premier Li Keqiang emphasized at a symposium with foreign experts that "the global scientific community should adhere to the principle that science must be cooperative and open" [?]. Research shows that after 2013, the number of global publications related to open science has shown a rapid growth trend, open science practices began to accelerate in 2016, and since 2017, global open science has entered a period of rapid development [?].

Existing research on open science practice mainly focuses on four aspects: (1) Academic research progress on open science at home and abroad, including domestic open science research progress [?], international open science research progress [?], research progress on open science ecosystems at home and abroad [?], current status of scientific data sharing research at home and abroad [?], and current status of open science data policies at home and abroad [?]. (2) International macro-level open science practice systems, including France's open science practice progress and top-level design [?], Europe's open science promotion and development system [?], the EU's open science practice system [?], the practice progress and characteristics of the US Center for Open Science [?], and Japan's open science development status [?]. (3) International micro-level open science practice programs, including the development status of international data journals [?], the development status of international open science communities [?], the current status and trends of scientific data sharing systems [?], characteristics of publications in international data journals [?], practice progress of scientific data and open sharing at home and abroad [?, ?], international data publishing progress [?], the application status of open data in different international information organizations [?], the development status of foreign social science open access academic journals [?], and the development status of foreign academic information open access [?]. (4) Domestic micro-level open science practice programs, including China's scientific data open sharing models and related standards [?], China's practice progress in scientific data open access [?], the current status of China's open academic journal publishing convergence [?], the development status of social science data open sharing [?], the progress of China's large-scale scientific instruments and equipment resources open sharing construction [?], the current status of domestic humanities and social science journals open access [?], and the development status of domestic open access [?]. While these achievements have promoted open science theoretical research and practical applications to a certain extent, they still have limitations: First, the research objects are relatively narrow, focusing on the practice progress of a few developed countries such as Europe, the United States, and Japan, with insufficient attention to other regions. Second, the research fields are overly concentrated, with open scientific data, open access journals, and data journals becoming hot topics, while insufficient attention is paid to open research infrastructure and open science policies and regulations. Third, there is a lack of comparative research results, with existing studies either analyzing foreign 典型案例 for enlightenment or proposing development suggestions through domestic surveys, rarely conducting comparative analysis of domestic and foreign practices at the same level.

Based on this, this paper selects four mature sub-fields of current open science development at home and abroad—open access journals, open scientific data, open infrastructure, and open science strategies—to conduct investigation and analysis, and analyzes and illustrates future trends of open science. This represents both a comprehensive review of typical open science practices at home and abroad and a benchmarking analysis of the shortcomings of China's open science practices. The subsequent structure of this paper follows the logical framework of Why-What-How: First, it analyzes the basic theory of open science from three levels—ideological schools, content systems, and practical significance—

to answer why we need to promote open science. Then, it reviews the progress of open science practices at home and abroad, compares the shortcomings of China's open science practices, and answers what practical content open science includes. Finally, it proposes China's open science development path, looks forward to global open science future trends, and introduces the Global Open Science Cloud initiative, answering how to develop open science.

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## 1. The Conceptual Connotation and Practical Significance of Open Science

From a historical perspective, the theoretical research and practical development of open science have varied across different periods, with its content and forms continuously improved through practice, gradually forming a new social and cultural concept. Different advocates have different understandings of open science [?], and similar understandings have aggregated to form different schools of thought on open science [?]: The cultural concept paradigm view of open science considers it an open expression of traditional closed scientific thinking [?, ?], while the knowledge innovation view considers it a knowledge production mechanism that participates in scientific and technological innovation [?, ?, ?, ?]. This paper agrees with the view that "open science refers to a new research method where the scientific community follows established conventions to open and share various elements in the scientific research lifecycle, allowing others to use them free of charge, in a timely manner, and freely, and promoting cooperation among researchers. This research method embodies concepts such as freedom, openness, cooperation, equality, and sharing, and its connotation includes multiple dimensions such as popularization, democratic rights, methodology, technology sources, and evaluation methods" [?].

Open science did not emerge as a completely innovative concept but evolved into a comprehensive conceptual system based on various related concepts and practices. Its content elements cover almost all aspects of scientific research and knowledge dissemination. Liu Guifeng et al. [?] believe that the specific content of open science includes open science policies, open access, open data, open resources, open peer review, etc. Kou Leilei et al. [?] incorporate citizen science, open innovation, Science 2.0, crowdsourcing, and crowdfunding into the scope of open science content. PARTHENOS [?] expands the content areas of open science to include open science clouds, open science skills and rewards, alternative metrics, and research integrity. Based on existing research classification methods, this paper argues that open science is an extremely inclusive ecosystem containing multiple types of resource elements such as policies, human resources, technology, tools, and facilities. Various 细分 concepts are not completely independent or mutually exclusive but are interconnected and distinct. Specifically, open notebooks, open education resources, open laboratories, open hardware, open source software, open data, open evaluation, crowdsourcing, and open storage are the most basic components of open science, which help achieve the overall goal of open science through forms such as open infrastructure, citizen science, open access, open publishing, and convergent science.

Open science originates from science itself, is practiced in society, and serves national strategies, with comprehensive theoretical and practical significance. (1) From the perspective of scientific research, open science fundamentally changes the dissemination model of scientific research, maximally eliminates technical barriers and financial difficulties in academic information flow, connects marginalized vulnerable groups and emerging technology agents, and forms new interactive communities with them. Through open science, utilizing collective intelligence to conduct scientific research not only improves individual researchers' achievements but also promotes the exchange of research theory and practice [?], which in turn drives scientific research forward. (2) From the perspective of social management, open science represents the disclosure behavior of innovation subjects toward knowledge and the continuous introduction process of innovation capabilities. This concept injects new vitality into technological innovation and social transformation, providing higher-level social welfare [?]. Open science practices in several fields are also of great significance for enhancing public cognition, broadening public horizons, exercising scientific thinking, and raising public awareness of intellectual property rights. (3) From the perspective of national strategy, open science can be considered an urgent need, a slogan, and a practical goal, summarizing all good wishes to achieve interaction between technological tools and traditional scientific undertakings through technical means [?]. The continuous adoption of innovative thinking methods, the continuous emergence of major scientific achievements, the steady improvement of public scientific literacy, and the inheritance of the scientific spirit will propel the country toward becoming an innovative nation and a world science and technology power.

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## 2. International Open Science Practice Dynamics

Open science basic theory defines its connotation and extension, presenting a rich content system. However, from a practical perspective, not all open science content elements have good conditions for practice. Through literature and network investigations, current international open science practices mainly focus on open science strategies, open infrastructure, open scientific data, and open access journals, corresponding to the top-level system, foundational conditions, material elements, and final products of scientific research, basically covering the scientific research lifecycle.

**2.1 Progress in Open Science Strategy Practices** Open science is not only a research paradigm but also an interaction between scientific tradition and information and communication technology tools, representing a breakthrough from the spirit of confidentiality to new incentive mechanisms. This breakthrough also drives open science from an academic movement to an international/national strategy [?]. Currently, countries worldwide are actively taking action on open science strategies, having introduced multiple policies that incorporate open science into research proposals and plans. Related practices mainly concentrate on top-level design, plan formulation, and roadmap development, which strongly promote the open science process forward.

(1) **Top-level Design**: In April 2012, the European Academies Science Advisory Council (ALLEA) published "Open Science for the 21st Century: A Declaration for All European Academies," calling on research funding agencies to fully implement open science principles [?]. In 2014, the Netherlands formulated the "Open Science and Research Plan" and established the National Coordination Federation of Open Science for a Knowledge Society [?]. In 2015, Japan released opinions on "Promoting Open Science in Japan" and established the Open Science Promotion Committee in 2017 [?]. In July 2018, the US National Academies of Sciences, Engineering, and Medicine released the report "Open Science by Design: Realizing a Vision for 21st Century Research," proposing the "Open Science by Design" framework [?]. In July 2019, the Serbian government passed the new Science and Research Act, recognizing open science as a fundamental principle of scientific research [?].

(2) **National Plan Formulation**: In 2016, the European Commission released the report "Open Innovation, Open Science, Open to the World," introducing actions already taken or being prepared in Europe, announcing the "European Open Science Agenda" and launching the "European Cloud Initiative" [?]. In February 2017, the Netherlands launched its national open science plan, publishing the "Dutch Open Science Declaration" and initiating the construction of the "National Platform for Open Science" [?]. In April 2018, France's Ministry of Higher Education, Research and Innovation released the "French National Plan for Open Science," making three commitments: open access publications, open access research data, and participation in European and international open science activities [?].

(3) **Roadmap Formulation**: Finland took the lead in developing an open science roadmap in 2014. In 2015, the European Commission listed open science as one of its strategic priority areas [?]. Subsequently, the Food and Agriculture Organization of the United Nations, the European Union, Poland, UNESCO, France, Canada, and other countries and international organizations began to develop and release open science-related roadmaps, mapping out the future development of open science from different aspects such as scientific research, hardware facilities, cloud infrastructure, and cultural construction, as shown in Table 1 .

**2.2 Progress in Open Infrastructure Practices** With the advancement of open science, scientists envision building a platform that integrates software and hardware compatibility to consolidate existing data resources, software codes, scientific reasoning, and problem descriptions. Research infrastructure has become one of the effective ways to realize this vision [?]. Since the 1990s, when the construction of research infrastructure sharing centers began [?], multiple national governments, international organizations, and research institutions have planned or invested in the construction of a new generation of research infrastructure. Important initiatives are shown in Table 2 .

The completed open infrastructure can be basically divided into five types [?]: open access infrastructure (represented by OpenAIRE), open research data infrastructure (represented by ARDC), open reproducible research infrastructure (represented by COS), open science evaluation infrastructure (represented by MOSP), and comprehensive open science infrastructure (represented by EOSC). Taking the international cooperation project Square Kilometre Array (SKA) radio telescope in the field of astronomy as an example, its application and construction are jointly completed by 11 core countries' regional data centers and more than 100 research institutions. It is the largest-scale astronomical experimental device ever built by humanity, integrating celestial observation, astronomical data collection, storage, processing, international cooperative research, and astronomical science popularization. Upon completion, it will create new opportunities for human exploration of the origin of the universe [?].

As can be seen from Table 2, countries worldwide have achieved remarkable results in open infrastructure construction, especially in the past decade when open research infrastructure construction has entered a "blowout" period. After nearly 30 years of development, the currently built open infrastructure has become an important foundation for scientific data collection, management, sharing, and preservation.

**2.3 Progress in Open Scientific Data Practices** Open Access (OA) has only taken the first step toward open science, but the scope of open science extends far beyond this. The scientific community expects to obtain scientific data resources such as raw data, pre-processed data, data processing procedures, and data processing tools from the early stages of the research process. Scientific data sharing is a necessary condition for public participation in scientific research, knowledge innovation, service quality improvement, and social progress [?], and also one of the necessary ways to enhance the democratic supervision, consultation, and participation of open science [?]. Current practices related to open scientific data mainly concentrate on data publishing, conference discussions, policy formulation, platform construction, and scientific research.

(1) **Data Publishing**: In 2009, *Earth System Science Data* was launched, becoming the first academic journal focusing on publishing data papers. Subsequently, international data journals such as *Scientific Data* (2014), *Geoscience Data Journal* (2014), and *Polar Data Journal* (2017) emerged.

(2) **Conference Discussions**: In 2012, the US National Research Council organized the "Symposium on International Scientific Data Sharing Cases

in Developing Countries" and published the proceedings [?]. In August 2014, the CODATA Task Group for Developing Countries, jointly with multiple international organizations, held the "International Symposium on Scientific Data Sharing for Science and Sustainable Development in Developing Countries" and unanimously adopted the "Principles for Scientific Data Sharing in Developing Countries" [?]. In September 2019, CODATA held the "International Symposium on Open Scientific Data Policy and Practice" in Beijing, discussing and releasing the "Beijing Declaration on Research Data," which proposed ten principles adapted to the new open science paradigm [?].

(3) **Policy Formulation**: In June 2017, Japan's Cabinet Office released the "Integrated Innovation Strategy" series of documents, proposing to implement a data-driven development strategy based on data sharing platforms [?]. In August 2017, the UK released the "New Data Protection Bill: Reform Plan," adding data portability rights and the right to be forgotten, making it easier for people to require institutions to provide personal data free of charge [?]. In May 2018, the General Data Protection Regulation (GDPR) officially came into effect, which is currently one of the strictest data protection laws in the world, creating an EU model for data protection [?].

(4) **Platform Construction**: There are not only domain-specific scientific data platforms such as "UN Data," "Africa Open Data," "IMF Database," and "OECD Library" [?], but also comprehensive scientific data platforms such as Dryad, eCrystals, and SRDA [?].

(5) **Scientific Research**: N. A. Vasilevsky et al. surveyed 318 academic journals and found that 21% of them explicitly required open scientific data as a necessary condition for paper publication [?]. A survey by the European Commission showed that as of October 2019, among 149 research funding agencies in 26 major countries worldwide, 41 explicitly required open scientific data and 22 encouraged it. Among 2,416 scientific data repositories globally, 2,281 showed full support for openness, and 120 allowed conditional openness [?].

**2.4 Progress in Open Access Journal Practices** In the Web 2.0 era, the communication mode of scientific research achievements has shifted from "completed upon publication" to "beginning upon release." Open Access (OA) has become a new mode and pathway for academic achievement dissemination, with its core being the use of internet technology to provide academic peers with the research results of scientific paper creators [?]. Current practices related to open access journals mainly concentrate on preprint platforms, open access initiative programs, open access weeks, open access action plans, and cooperation between academic institutions and publishers.

(1) **Emergence of Preprint Platforms**: The practical implementation of

open access began with preprint platforms, with typical representatives including arXiv, medRxiv, bioRxiv, engrXiv, ChemRxiv, and Figshare. Taking arXiv as an example, from its establishment in 1991 to January 2020, it has stored more than 1.6 million research papers with over 260 million downloads.

(2) **Rise of Open Access Initiatives**: After entering the 21st century, driven by the "Budapest Open Access Initiative" (February 2002), multiple related initiatives have been launched internationally with trial actions, such as the "Glasgow Declaration on Information Services and Knowledge Freedom Access" (August 2002), the "Bethesda Statement on Open Access Publishing" (June 2003), and "OA2020: An Initiative for Large-scale Academic Journal Open Access."

(3) **Global Open Access Week**: Since 2009, Open Access Week (OA Week) has been held globally. After more than ten sessions, the United States, United Kingdom, Australia, Japan, Spain, China, and others have become active practitioners of OA Week [?].

(4) **Open Access Action Plan Formulation**: Since 2012, open access has been listed as one of the action plans by relevant international organizations. The Global Research Council (GRC) has successively released multiple guiding documents such as the "Action Plan for Open Access Publications" and "Implementation Survey of GRC Open Access Publications Action Plan" [?]. In September 2018, the European Commission and others launched "Plan S," requiring all scientific research results funded by public money to be published through open access after 2020 [?].

(5) **Cooperation Between Academic Institutions and Publishers**: In December 2019, the Dutch University Association and other institutions reached a framework agreement with the data publisher Elsevier, making all Elsevier-owned journals completely free to Dutch researchers and supporting researchers to publish open access papers [?]. In June 2020, the University of California signed a four-year open access agreement with Springer Nature, setting a North American record for OA publication orders by research institutions [?]. From preprint platforms to OA initiatives, from OA Week to Plan S, open access journals have basically formed five models during their development: green OA, gold OA, brown OA, black OA, and hybrid OA [?], with different models representing different degrees of "openness."

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## 3. Localization Considerations for Open Science Practice

**3.1 Review of China's Open Science Practices** Facing the international wave of open science, various stakeholder institutions in China are also taking active actions. Similar to foreign practices, China's current open science practices mainly concentrate on open infrastructure, open scientific data, and open access journals.

**3.1.1 Progress in Open Infrastructure** Focusing on the open sharing of scientific data and scientific papers, China has actively built open research infrastructure, forming a practice situation that is "mainly open data infrastructure, supplemented by open research instruments and equipment + open literature infrastructure."

(1) **Open Data Infrastructure**: During the "12th Five-Year Plan" period, one of the achievements of the Chinese Academy of Sciences' "China Science and Technology Resource Integration and Sharing Project"—the Chinese Academy of Sciences Data Cloud—had 15.7% of its user groups from overseas. In 2016, Academician Guo Huadong initiated the "Digital Belt and Road" (DBAR) International Science Program, participated in by 48 countries and international organizations, aiming to provide information decision-making support for the Belt and Road Initiative through the construction of an Earth big data platform [?]. Some universities are also actively building open research data infrastructure [?], such as Fudan University's Social Science Data Platform, Wuhan University's University Scientific Data Sharing Platform, Huazhong University of Science and Technology's China University Social Science Data Center, and Peking University's Open Research Data Platform.

(2) **Open Research Instruments and Equipment**: In 2015, the State Council issued the "Opinions on Opening National Major Research Infrastructure and Large-scale Research Instruments to Society" [?]. In February 2018, the Ministry of Science and Technology, together with the Ministry of Finance, formulated the "Management Measures for National Science and Technology Resource Sharing Service Platforms" to promote the opening and sharing of science and technology resources to society by regulating the behavior of science and technology resource sharing service platforms [?]. On June 5, 2019, the Ministry of Science and Technology released the "List of Optimized and Adjusted National Science and Technology Resource Sharing Service Platforms," optimizing and adjusting the original national science and technology resource sharing service platforms. The temporarily deployed 20 national science data centers have developed into important infrastructure for scientific data collection, management, sharing, and preservation [?]. From June to September 2020, the Ministry of Science and Technology, together with multiple departments, conducted evaluation and assessment work on the sharing of research infrastructure and instruments in central-level universities and research institutes [?].

(3) **Open Literature Infrastructure**: In 2013, the Chinese Academy of Sciences launched the construction of the GoOA open access paper discovery platform, which currently provides service products such as open access paper discovery platforms, open access journal submission star rec-

ommendations, and open access journal TOP rankings [?]. In June 2016, the ChinaXiv preprint platform of the Chinese Academy of Sciences was officially launched. The platform has currently received nearly 15,000 scientific papers from various disciplines [?], and the Institute of Semiconductors of the Chinese Academy of Sciences has also established the world's first semiconductor field preprint platform, JOSarXiv.

**3.1.2 Progress in Open Scientific Data** Starting from joining the World Data Center (WDC) in the late 1980s to the launch of the "Scientific Data Sharing Project" pilot at the end of 2001, and then to participating in signing the "OECD Declaration on Open Access to Publicly Funded Research Data," China has continuously taken action in scientific data open sharing, gradually forming multiple open sharing models such as data platforms, data publishing, crowdsourced processing, and data trading [?]. Specific practices mainly focus on "data publishing + policy release + series activities."

(1) **Data Publishing**: In June 2014, the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences built the "Global Change Research Data Publishing System." Based on this system, it successively established the data journals *Journal of Global Change Data* (in Chinese and English) and *Global Change Data Repository* [?]. In June 2016, the first and currently only multidisciplinary specialized data journal in China—*China Scientific Data*—was officially launched [?], which has published more than 300 data papers. Journals such as *Acta Geographica Sinica (Data Version Supplement)*, *Geology in China (Data Version Supplement)*, *Big Earth Data*, and *Library Journal* have also gradually supported the publication of domain scientific datasets.

(2) **Policy Release**: In March 2018, the State Council issued the "Measures for the Management of Scientific Data," establishing the principle of "openness as the norm, non-openness as the exception" for scientific data, guiding open sharing of scientific data from the national level [?]. In February 2019, the Chinese Academy of Sciences issued the "Measures for the Management and Open Sharing of Scientific Data of the Chinese Academy of Sciences (Trial)" [?]. In June 2019, the National Microbial Science Data Center, jointly with domestic microbial research institutions, sequencing institutions, societies, and journals, initiated the establishment of the Microbial Science Data Sharing Alliance [?]. In July 2019, the Chinese Academy of Agricultural Sciences issued the "Measures for the Management and Open Sharing of Agricultural Scientific Data of the Chinese Academy of Agricultural Sciences" [?].

(3) **Series Activities**: Since 2013, the National Science and Technology Infrastructure Center has held the "Sharing Cup" Science and Technology Resource Sharing Service Innovation Competition annually, carrying out innovation and entrepreneurship practice activities for university students, researchers, and innovative enterprises nationwide. Since 2014, the CO-

DATA China Committee has organized the "China Scientific Data Conference" annually to discuss theories and technologies of scientific data openness. Since 2016, the National Science and Technology Infrastructure Center has organized the compilation of the "National Scientific Data Resources Development Report" annually to take stock of China's scientific data resources [?]. Since 2018, Peking University has hosted the "National University Data-Driven Innovation Research Competition," encouraging students from various disciplines to conduct innovative research based on shared data.

**3.1.3 Progress in Open Access Journals** China started relatively late in open access to academic journals, with current practices mainly focusing on "conference holding + policy release + platform building."

(1) **Conference Level**: In October 2010, the Chinese Academy of Sciences and the German Max Planck Society jointly held the "8th International Conference on Open Access," with both parties expressing their intention to promote the establishment of the Global Research Council for Open Access [?]. Since 2012, "China Open Access Week" (China OA Week) has been held for nine sessions. At the end of May 2014, the Chinese Academy of Sciences and the National Natural Science Foundation of China jointly hosted the 3rd GRC Annual Meeting, with "open access to scientific publications" being one of the annual themes. Premier Li Keqiang stated in his speech at the conference that China supports the establishment of an open access mechanism for scientific knowledge [?].

(2) **Policy Level**: In early May 2014, the Chinese Academy of Sciences and the National Natural Science Foundation of China respectively released policy statements on open access to papers from publicly funded research projects, both explicitly requiring that funded project results must be stored in institutional repositories and made open to society within 12 months after publication [?].

(3) **Platform Level**: In early 2018, the National Press and Publication Administration launched the "OSID Open Science Initiative." Each journal paper included in the OSID initiative is automatically assigned an OSID code, through which readers can access various related content such as audio introductions, basic data, full text, and author-reader interactive Q&A [?]. In May 2020, the Documentation and Information Center of the Chinese Academy of Sciences signed an agreement with Oxford University Press to support Chinese Academy of Sciences members to access and publish open access papers, marking China's first open publishing transformation agreement [?].

**3.2 Shortcomings of China's Open Science Practices** Although China has actively practiced open science and achieved certain results, compared with European and American countries, China's overall open science development level still has room for improvement in institutional planning, cultural atmosphere, degree of openness, and brand reputation.

(1) **Lack of Top-level Planning**: According to investigations, the highest-level policy document for open infrastructure in China is the "Management Measures for National Science and Technology Resource Sharing Service Platforms," while the highest-level policy document for open scientific data is the "Measures for the Management of Scientific Data." However, there are still no national-level policy systems for open science as a whole and for important open science elements such as open access journals, open source software, open evaluation, and open publishing, let alone an overall open science development plan or roadmap to guide the entire field.

(2) **Weak Open Atmosphere**: Overall, China's open science practice subjects are basically limited to a few institutions such as the Ministry of Science and Technology, the National Natural Science Foundation of China, and the Chinese Academy of Sciences. Other ministries, research institutions, and universities have low participation enthusiasm and degree. Currently, only the Chinese Academy of Sciences explicitly supports preprint results, while other research management institutions only recognize research results published through traditional channels [**?**].

(3) **Low Degree of Openness**: Although open access journals have been advocated in China for many years, most researchers still pay both academic journals and literature publishers. The open infrastructure is mostly precision equipment that is difficult for ordinary people to use, while conventional instruments and equipment remain locked away [**?**]. The "Open Science Initiative (OSID)" is a public welfare activity initiated by the National Editorial Society [**?**], targeting only the academic journal industry but claiming to be "open science," which is somewhat exaggerated.

(4) **Weak Brand Reputation**: Looking at international landmark achievements/events in open science, Chinese institutions are rarely present and have weak presence in many fields. Taking institutional repositories as an example, by the end of 2020, China's institutional repositories in the OpenDOAR directory only numbered 60, accounting for only 6.6% of the US number [**?**]. Currently, among the seven general-purpose data repositories recommended by Springer Nature, only ScienceDB is independently built by China.

These shortcomings are not caused by the behavior of any single group but are the result of multiple factors: (1) For a long time, China has mostly followed the footsteps of developed countries in important international open science affairs, failing to form an open science theory and practice system with Chinese characteristics and to grasp absolute discourse power in the global open science system. (2) Society has not truly formed an open science culture. Under the influence of altruistic motives, profit-seeking motives, reputation and respect motives, and team emotional motives, traditional closed scientific thinking remains deeply rooted, and the public has not formed a broad cultural consensus on open science [?]. (3) Stakeholders have different understandings of the conceptual connotation of open science, falling into knowledge misconceptions such as open science equals open access journals, open science equals open data, and open science equals open infrastructure. A one-sided view of open science blurs its content system and element boundaries, and differences in understanding the importance and necessity of open science lead to different departments acting independently or even constraining each other. (4) China has indeed failed to produce open science achievements with global influence, and domestic institutions have not timely packaged and promoted existing practical achievements, which may also result in weak Chinese voices. For academic influence considerations, domestic scholars prefer to choose journals, repositories, and software tools with certain international reputations when publishing their achievements. (5) The current intellectual property system lags behind the needs of open science practice, especially in the process of scientific data open sharing, where rights to data collection, preservation, knowledge, use, and ownership become blurred, which may undermine researchers' intrinsic motivation and affect their sharing enthusiasm. In addition, privacy issues, security issues, and ethical issues are also important factors hindering open science practice, such as not being able to share personal health, spatiotemporal trajectory, and consumption transaction data without consent to avoid privacy leakage [?], forcing important scientific data to be stored on domestic platforms first to avoid data flowing abroad [?], and introducing social evaluation and promoting technological neutrality to assess ethically controversial scientific research results [?].

**3.3 China's Open Science Development Path** Open science is not only an idealistic concept but also a complex systematic undertaking. Achieving complete open science remains difficult [?], as resources, technology, and institutions are all indispensable. The sound development of open science requires systematic promotion from multiple aspects, including national strategic planning, social environment cultivation, and individual concept transformation.

**3.3.1 National Level: Formulate Open Science Promotion Strategy** UNESCO has listed open science as one of its important agendas for the next decade and initiated the formulation of the "UNESCO Recommendation on Open Science" in 2019, recommending that member states promote it according to their national conditions. Against this backdrop, China needs to clearly recognize the global development trend of open science, take the UN 2030 Agenda for Sustainable Development as the ultimate goal, invite stakeholders to discuss and judge the development trend of world open science in the next 10-15 years, and formulate a national strategic plan for open science with Chinese characteristics based on China's open science practice status. Several existing open science roadmaps can provide reference templates for us.

**3.3.2 Social Level: Create an Open Science Cultural Environment** All stakeholder institutions must effectively improve their political positioning, accelerate the implementation of the open science national strategy from the aspects of organizational structure, supporting measures, human and financial resources, establish a national open science leadership/guidance group composed of national ministry leaders and domain experts, formulate 3-5 year short-term open science development plans in several key fields, select several representative institutions to conduct 1-2 year open science pilot projects with good publicity and promotion, formulate detailed and specific open science evaluation and assessment systems and incentive mechanisms, and allocate special funds for open science to create a good cultural atmosphere where "everyone is a participant in open science, and everyone is a beneficiary of open science."

**3.3.3 Individual Level: Enhance Open Science Skills and Literacy** Frontline researchers must master the use skills of open source software tools, open source data repositories, and research crowdsourcing platforms, and be able to handle issues such as scientific resource acquisition, scientific data processing, scientific paper writing, and research result publication calmly. Research managers must enhance their ability to track hotspots, understand policies, and plan directions, be able to sensitively capture major open science events, comprehensively convey national policy documents, and accurately formulate open science implementation plans for their fields/units. Research service personnel must keep up with international open science development trends, timely publicize the latest open science policies, recommend quality open science resources, publish the latest open science achievements, and assist in resolving intellectual property disputes.

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## 4. Future Exploration of Open Science

**4.1 Future Trend Outlook for Open Science** Looking at the global development trend of open science, driven by multiple factors such as demand, policy, and technology, the connotation and extension of open science continue to deepen and expand, and its future development trends are becoming increasingly clear. Figure 1 [Figure 1: see original paper] outlines an idealized future scenario for open science.

**4.1.1 Globalization of Open Concepts** The challenges facing scientific development are global, and the scientific community has a stronger demand for a global rule framework covering all levels of open science. The complexity of scientific issues and social challenges such as the UN Sustainable Development Goals, the COVID-19 pandemic, and global climate change has exceeded the processing capacity of individual countries, institutions, and disciplines. All humanity is a community with a shared future, and the urgent priority is to ensure that all countries and regions form a unified opinion on open science issues. In early 2019, the International Science Council (ISC) proposed the three-year action plan "Advancing Science as a Global Public Good" [?]. During the 40th UNESCO General Conference in November 2019, 193 member states decided to formulate the "UNESCO Recommendation on Open Science" to adopt universally acceptable open science policy recommendations and propose specific measures for open science [?]. In 2020, the European Commission also presented a vision for the next decade of open science [?], stating that "by 2030, open science will have become a reality, and researchers worldwide will have a series of new opportunities to participate in global scientific research."

**4.1.2 FAIRification of Open Resources** In the data-driven research paradigm, automated methods, artificial intelligence technologies, and supercomputing software are used to process vast and dispersed interdisciplinary resources. The use of these technical methods requires on-demand, ubiquitous, and seamless supply of research resources. However, the reality is that some descriptive text, images, and tables are still difficult for computers to recognize, read, understand, and interoperate [?]. In January 2014, the FAIR principles were proposed, with the main idea being to assign a globally unique data identifier (DID) to each digital object, making research resources more easily Findable, Accessible, Interoperable, and Reusable by machines, ultimately forming a FAIRified data and service network [?]. Subsequently, stakeholders launched the GO FAIR movement, actively promoting the implementation of FAIR principles through activities such as changing existing culture, training data curators, and building technical standards. The EU has adopted the FAIR principles as the basic principles for future research environment construction and policy formulation, and the European FAIRsFAIR project for FAIR data practice cultivation was launched in March 2019.

**4.1.3 Ecologization of Open Systems** The essence of open science is an ecological chain based on open data, where stakeholders break through conditional barriers to conduct in-depth knowledge analysis and reuse, and collaboratively participate in scientific and technological innovation [?]. From current practices, various levels of open science are still relatively fragmented and have not formed a comprehensive ecosystem. Countries worldwide are actively advocating for universal participation to jointly build an open science ecosystem framework with positive feedback mechanisms and mutual benefits. This system framework will provide an environment for creating, managing, and maintaining open science initiatives, forming an open network composed of stakeholders with similar goals. Each participant plays different roles in the network, directly or indirectly generating, providing, or consuming research resources (such as software tools, computing services, infrastructure, academic activities, policy systems, etc.) [?]. Through specific connections with other open networks, the collaboration and competition among participants ultimately promote the self-"evolution" of the open science ecosystem.

**4.1.4 Cloudification of Open Operations** Open science participants are distributed globally. If all matters were conducted through offline exchanges, it would be inefficient and costly. Therefore, there is a demand for remote real-time interactive collaborative research methods, and increasingly mature cloud service models provide possibilities for cloud-based processing of open science affairs [**?**]. Taking the China Science and Technology Cloud (CSTCloud) as an example, it currently provides computing leasing, storage space, network bandwidth, platform communities, scientific software, operation and maintenance, data information, security certification, and other services for numerous disciplinary fields. It has supported multiple major research projects, initially showing characteristics of a "research proprietary cloud," "open cloud," and "global cooperation cloud." The global COVID-19 prevention and control practice has shown that when facing sudden major public health events, it is necessary and feasible to conduct research data transmission, federated analysis, result sharing, and discussion exchanges through the cloud. Resource open sharing and cross-domain collaborative innovation will become the new normal in society [**?**].

**4.2 Practical Exploration of the Global Open Science Cloud** Given the dynamic, diversified, and immediate demands of open science for research resource supply forms, scientists are exploring the establishment of a global cooperation framework to coordinate and integrate various open science resources. In October 2019, the CSTCloud team innovatively proposed the concept of building a "Global Open Science Cloud" (GOSC) during the CODATA Beijing Conference. Figure 2 [Figure 2: see original paper] shows the conceptual framework of GOSC.

The vision of GOSC is to unite digital infrastructure, technical experts, data scientists, policymakers, policy researchers, virtual academic communities, and other stakeholders through key actions such as unified policy systems, interoperability protocols, sustainable mechanisms, and typical application scenarios. Together, they will design research architectures, develop supporting software, and deploy test platforms to connect open science clouds in different countries and regions, building a transcontinental federated digital infrastructure and virtual research environment for global cooperation and open science. This will provide cloud services such as network interconnection, computing federation, data FAIRification, and authorized authentication interaction for global researchers [**?**]. The ultimate mission of GOSC is to maximize the utilization of research resources worldwide, assist in bridging the infrastructure and technical capability gaps between different groups, support long-term global scientific cooperation, and truly promote the sustainable development of international scientific endeavors.

After the GOSC initiative was proposed, it received broad support from multiple international organizations worldwide, and many research institutions actively responded and participated in GOSC construction. Figure 3 [Figure 3: see original paper] shows some representative events in GOSC construction.

Currently, CSTCloud has achieved interoperability of authorized authentication systems with the European Grid Infrastructure (EGI), a core institution of EOSC. Subsequently, both parties will continue to cooperate in building transcontinental open science cloud environments, developing transcontinental cloud federation core technologies, and researching open science cloud governance policies [**?**]. In the future, GOSC will seek to establish a broader trust-based cooperation dialogue mechanism globally, continuously promote global research resource collaborative sharing and extensive interconnection and interoperability of open science cloud federation infrastructure, and provide support services for the Belt and Road Initiative.

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### Conclusion

The emergence of open science is driven by both internal motivations from science itself and external pushes from policies, technologies, and resources, and it is mutually reinforcing with related practical activities. Open science is rising with the trend, which is significant for both scientific research itself and stakeholders. Through open science, the lifecycle of scientific research is greatly shortened, the visibility and participation of research activities are enhanced, the speed and efficiency of research output are significantly improved, some new scientific problems are discovered and solved, and various elements converge to form an open science community. Although the concept of open science has basically taken root in people's hearts, the current domestic and international open science practices still mainly focus on open science strategies, open infrastructure, open scientific data, and open access journals, with insufficient coverage to fully demonstrate the complete picture of open science. Barriers to open science still exist, and achieving complete open science remains difficult. Compared with the good practice results in Europe and America, China still has room for improvement in institutional planning, open atmosphere, degree of openness, and brand reputation. This requires multi-level efforts from the nation, society, and individuals to explore a development path suitable for China's national conditions around the entire process of open science. Looking to the future, the practical exploration of open science will never cease. Its prospect is that the global scientific community will reach a consensus on open science, with resources, technologies, tools, policies, and human resources converging to form a complete open science ecosystem, and scientific achievements will achieve FAIRified interaction globally through the cloud.

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Wen Liangming: Responsible for topic selection, proposed the paper framework, determined the writing 思路, and wrote the initial draft.
Li Yang: Adjusted the paper framework, participated in network investigation, revised the paper, and finalized the manuscript.
Guo Lei: Responsible for network investigation and subsequent revisions.

**The Practice Progress and Future Exploration of Open Science at Home and Abroad**

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**Abstract:** *[Purpose/Significance]* Timely tracking and analyzing the practical progress of open science both domestically and internationally can provide decision-making support for science and technology management departments to adjust open science policies and plan open science directions. *[Method/Process]* This paper summarizes current research and practice in open science across four dimensions: the conceptual connotation and practical significance of open science, international open science practice progress, domestic open science practice progress, and future development trends of open science. *[Results/Conclusions]* Open science represents the inevitable evolution of knowledge from seclusion to innovation. The international community has implemented sound practices in open science strategies, open infrastructure, open scientific data, and open access journals. China still needs improvement in institutional planning, cultural cultivation, degree of openness, and brand reputation. In the future, open science will develop toward globalization, FAIRification, ecologicalization, and cloudification.

**Keywords:** open science; scientific community; Global Open Science Cloud; FAIR principles; open ecology

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