Framework and Implementation Pathways for Advancing Open Science in Europe: Postprint

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Date: 2023-04-01T16:15:54+00:00

Abstract

[Purpose/Significance] This study explores the drivers and main practices that propel the European open science process, aiming to identify its inherent logic, promotion system, and practical pathways, thereby providing decision-making references for the development and practice of open science in China.

[Method/Process] Through web-based survey methodology, this paper reviews the EU's promotion of open access since 2006 and its recent open science practices, summarizing the concepts and practices that drive open science development.

[Results/Conclusions] The development of European open science features a well-established policy system and pragmatic practical pathways. China can adapt to its national conditions and selectively draw on these experiences to promote the development of open science.

Full Text

The System and Practice Path of Open Science Development in Europe

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Abstract: [Purpose/Significance] This paper explores the motivations and main practices driving the European open science process, identifies the underlying logic, system, and practical path of its development, and provides

decision-making references for the development and practice of open science in China. [Method/Process] Through network investigation, this study summarizes the evolution of EU policies from promoting open access in 2006 to recent open science practices, and synthesizes the concepts and practices that drive open science development. [Result/Conclusion] The development of open science in Europe features a sound policy system and pragmatic practical path. China can selectively draw on this experience in light of its national conditions to promote open science development.

Keywords: open science; open access; open data

Driven by digital technologies and scientific globalization, open science has become a new trend and direction in the international transformation of scientific research paradigms and scientific organization. The core practices of open science encompass the entire research cycle, including data, publications, and participants—ranging from open access to research outcomes, to open research data, and further to openness of all outputs across the full spectrum of research processes, including scientific methods, software, and workflows for comprehensive transparency. This transformation also involves corresponding changes in scientific communication and evaluation methods, such as open peer review and open scientometrics, extending to the general public to support citizen science through open collaboration. Against this backdrop, the research process becomes more open, transparent, networked, collaborative, and reproducible, accelerating scientific communication and knowledge transfer.

Internationally, the promotion of open science is in full swing, with significant progress in open access to research papers and data. The number of open access publications has grown rapidly [1], scientific data resources are increasingly abundant [2], and policies [3] and data reuse mechanisms [4] surrounding research data openness are continuously improving. Data publishing journals and data sharing platforms [5] continue to emerge. Some countries have directly formulated national open science plans—for example, the Netherlands [6] and France [7] launched their national open science plans in 2017 and 2018 respectively, focusing on three aspects to facilitate the transition to an open science system: open access to scientific publications, optimal use and reuse of research data, and adjustment of evaluation and reward systems. Major funding organizations have all formulated and released explicit policies supporting open science and open access.

China's research on open science remains largely in the stage of introducing international advanced experiences, with relatively scattered policies and initiatives, and no systematic development framework or path. While the state and research funding agencies have issued some measures to promote open science development, these are basically guiding principles that do not form a coherent system, and their driving effect on open science is not significant. Examples include the "Administrative Measures for Scientific Data" issued by the Gen-

eral Office of the State Council in March 2018 [8], and the position statement issued in December 2018 by the National Natural Science Foundation of China, the National Science and Technology Library, and the Documentation and Information Center of the Chinese Academy of Sciences in support of the open access S Plan initiated by Europe, committing to adopt various flexible and inclusive measures to achieve immediate open access to research results funded by public funds [9]. Domestic academic follow-up on open science has mostly focused on analyzing the origins, driving factors, advantages, and obstacles of the open science movement [10-12], and introducing certain advanced foreign experiences, such as open access policies, institutions, and infrastructure planning [13-17], without conducting in-depth analysis of the national system and path for promoting open science development. This paper will explore the motivations and main practices driving the European open science process, expanding the research object from single practical experiences to a series of policy-guided, logically coherent actions, in order to identify the internal driving forces of European open science development and provide decision-making references for China's open science development and practice.

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1. The Development Process of European Open Science

1.1 Motivations for European Open Science Development

The core motivation for Europe's open science development is to fully utilize data-driven science, promote the free flow of knowledge, and ensure Europe's global leadership in strategic fields. This concept can be traced back to a 2006 European Community-funded study on the European scientific publication market, which identified the dissemination and access to research results as pillars for the development of the European Research Area (ERA) [19]. In 2016, the EU Council proposed the "transition toward an open science system" [20], marking a landmark event in European open science development. The development of open science in Europe has deep practical backgrounds and internal reasons. From a practical perspective, Europe's economic development has been weak in recent years, and increasing investment in research and innovation is seen as a means to solve economic difficulties, boost employment, and promote economic growth. In terms of promoting scientific development, the open science process is more transparent, efficient, and verifiable, capable of accelerating knowledge production, expanding research reuse, and promoting scientific development. Economically, open science helps accelerate technological innovation and drive economic growth. It is estimated that by 2020, massive open research data will increase the GDP of the EU-28 by 1.9% [21]. From a social perspective, on the one hand, the public outside the scientific community has the right to see the results of research they fund, better reflecting investment value; on the other hand, social organizations, teachers, medical professionals, and citizens can all benefit from easy access to scientific research information, thereby better promoting science at all levels of society.

Overall, Europe promotes open science development for three main reasons: first, to enable open access to knowledge within the European Research Area, avoiding waste and meaningless consumption caused by duplicate research; second, to make knowledge flow freely, sustainably, and accessibly for reuse, thereby contributing to European economic growth and better responding to new challenges in the digital age; and third, to accelerate innovation and knowledge discovery, combining scientific development with innovation and economic growth, integrating open innovation with open science to seek development in an open scientific and innovation paradigm.

1.2 The Development Process of European Open Science

Overall, Europe's open science development process can be divided into two stages:

(1) Recognizing the positive role of free knowledge circulation in innovation and economic growth, and promoting open access development (2006-2014). Maximizing open access to scientific publications and data is an important foundation and early stage of open science, which has deepened open science concepts and practices. First, against the backdrop of the global open access movement, to evaluate the evolution of Europe's scientific publishing market and discuss measures that could be taken at the European level to improve access to scientific publications, the EU released the "Study on the Economic and Technical Evolution of the Scientific Publication Markets in Europe" in 2006 [19], pointing out that disseminating and accessing research results is a pillar of European Research Area development and that the EU should propose policy recommendations to improve open access. Second, subsequently, the EU's 7th Research and Innovation Framework Programme (FP7), launched in August 2008, designated research outcomes in seven fields as open access pilots, requiring that final versions of published or peer-reviewed papers resulting from funded projects be deposited in online repositories, with maximum efforts to ensure open access to these articles [22]. Third, in 2010, the European Commission proposed the "Europe 2020 Strategy for Smart, Sustainable and Inclusive Growth," with the "European Digital Agenda" and "Innovation Union Initiative" as two flagship programs. The European Digital Agenda, proposed against the backdrop of rapid digital economy development, is an open data policy covering all information produced, collected, and purchased by EU public institutions [23], and subsequently adopted a package of open data solutions, proposing to extend the scientific publication open access pilot to all areas of the Horizon 2020 (H2020) program and to require open access to research data [24]. The Innovation Union Initiative committed to making open access to publications a general principle for projects funded by EU research framework programs [25]. Fourth, based on the European Digital Agenda and Innovation Union strategy, the EU proposed a complete set of recommendations for access to scientific information in 2012, pointing out that member states, research funding agencies, researchers, publishers, universities, libraries, innovation in-

dustries, and society as a whole need to work together to establish a European scientific information system adapted to the digital age, in order to achieve the EU's "Fifth Freedom"—the free flow of knowledge [26]. Fifth, the subsequent Horizon 2020, Europe's largest research and innovation program, gradually developed free access to funded project research results into a mandatory principle and open data into a default option [27].

(2) The development stage of promoting a comprehensive open science system (post-2015). The EU recognizes that open science can make science more efficient and transparent, strengthening the connection between science and society, and has begun comprehensively promoting the transformation of scientific research and innovation toward openness and democratization. Europe's open science development system includes three core components: open access to scientific publications and optimal use and reuse of research data; building supporting open science infrastructure; and establishing supporting evaluation, reward systems, and incentive mechanisms to motivate researchers to engage in open science practices and align them with open science goals. Among these, open access to scientific publications and open research data are the core, open science infrastructure is the key element, and supporting evaluation, reward systems, and incentive mechanisms are the guarantee. Other aspects of open science, such as open education, are not detailed in this paper as Europe has not yet made them development priorities.

The years 2015-2016 were crucial for demonstrating the connotation, importance, and strategic position of open science in Europe, and for building the open science system. First, the European Commission's Horizon 2020 2014-2015 Work Programme on "Science with and for Society" [28] began laying out the path from "open access" to "open science," linking scientific development with social responsibility, specific innovation, and economic growth potential, and incorporating open science elements into the formulation of responsible research and innovation policies. Second, in 2015, the European Commission set three goals for research and innovation policy: open innovation, open science, and openness to the world, envisioning the creation of knowledge through global cooperation by promoting openness in Europe's research and innovation system [29]. This goal evolved in 2016 into "Open Innovation, Open Science, Open to the World—A Vision for Europe," elevating it to a strategic goal for Europe's scientific landscape [30]. Third, during its EU presidency, the Netherlands made open science one of its main priorities and proposed the "Amsterdam Call for Action on Open Science," stating that Europe needed to accelerate its transition to open science and that every member state should develop a national open science plan [31]. This action plan directly led to the European Council's adoption of the "Transition to an Open Science System" resolution, in which the Commission, member states, and stakeholders reached agreement on promoting open science, officially launching Europe's transformation toward an open science system. The resolution stated that unnecessary legal, organizational, and financial obstacles to accessing publicly funded research results should be eliminated as appropriate to achieve optimal knowledge sharing. By 2020, all

publicly funded scientific publications should be fully open access, and targeted action plans should be formulated to ensure the long-term sustainability of research infrastructure [32]. Fourth, in April 2018, the European Commission released revised recommendations on access to and preservation of scientific information, expressing political support for EU member states transitioning to open science and recommending that member states not only monitor but also formulate and implement clear OA policies in their national action plans [32].

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2. Main Measures for Promoting Open Science Development in Europe

Europe's main measures for promoting open science are reflected at both strategic and practical levels. At the strategic level, the EU has incorporated open science development into major European policy frameworks such as the European Research Area (ERA) strategy, the Digital Single Market (DSM) strategy, and the "Open Innovation, Open Science, Open to the World" strategy. At the practical level, the EU provides policy platforms, monitoring, reporting, training, and other support services and auxiliary measures for open science development.

2.1 Europe's Strategy for Promoting Open Science Development

2.1.1 Open Science as a Strategic Priority for the European Research Area The European Research Area (ERA) strategy is a policy that promotes economic growth, cross-border cooperation, job creation, and optimal circulation, access, and transfer of scientific knowledge. It helps utilize resources efficiently and improve research investment returns. The ERA policy document "Strengthening the Partnership for Excellence and Growth in the European Research Area" [33] clearly states that optimal circulation and transfer of scientific knowledge is crucial to the ERA and should provide publicly funded knowledge to researchers and the private sector to enhance their knowledge base and reduce regional disparities. The document establishes "optimization of scientific knowledge exchange, access, and transformation" as one of five priority development areas for the ERA. This priority evolved in the 2015-2020 ERA development roadmap [34] into "achieving better exchange and transfer of scientific knowledge: implementing knowledge transfer policies at the national level to promote the development and utilization of scientific outcomes, and ensuring open access to publications and data in an open science environment." Open access can promote efficient ERA development, and in turn, the ERA promotes the transition to open science by prioritizing open access.

2.1.2 Open Science as a Driver of Europe's Digital Single Market Development The Digital Single Market (DSM) refers to an area where businesses and individuals can access and conduct online activities under fair compe-

tition conditions, with high consumer protection. The European Commission's May 2015 report on "A Digital Single Market Strategy for Europe" [35] emphasized the importance of science and research for promoting innovation and the importance of data dissemination as a catalyst for economic growth, innovation (especially for SMEs and startups), and society as a whole. The current Digital Single Market is characterized by high levels of research and innovation, and open science has become an important factor driving its development. In the mid-term review of the Digital Single Market strategy, the European Commission proposed advancing the construction of the European Open Science Cloud to further improve the strategic goal of "accessibility and reusability of public and publicly funded data," with member states providing strategic and political support for open science development. The European Parliament's report "Toward a Digital Single Market" called on the European Commission to cooperate with all relevant stakeholders to develop an action plan to establish the European Open Science Cloud by the end of 2016 [36].

2.1.3 Open Science as a Core Goal of Europe's Future Research and Innovation Strategy Open science is one of the three goals of EU research and innovation policy and a core component of open innovation. Linking science with innovation enables stakeholders to interact in new forms and achieve co-creation. Open innovation involves broader participants and freer knowledge circulation to create a stronger market culture and shared social and economic value. The focus of both open innovation and open science can be placed either on the successful commercialization of research results or on the benefits of public goods such as information sharing for businesses and society. The proposal of the "Open Innovation, Open Science, Open to the World" strategy will contribute to greater research integrity, openness, inclusiveness, and network collaboration, and will affect scientific quality, making science more efficient, more reliable, and better able to respond to the challenges of the times, promoting co-creation and open value.

2.2 Europe's Practice in Promoting Open Science Development

2.2.1 Fully Promoting Open Access The EU Commission's development goal for open access is to maximize the impact of publicly funded scientific research as much as possible and to develop a transparent, competitive academic exchange market. The EU has provided continuously expanding and deepening policy support for open access development, transitioning from general, brief principles to clear and specific implementation guidelines, some of which have been elaborated in the policy section on promoting open science development. The FP7 framework program piloted open access in specific fields and created the pan-European information system OpenAIRE in 2009 to provide services for discovering, storing, linking, and analyzing research results in all disciplines to implement EU policies on promoting science and research. In the Horizon 2020 framework program, open access to publications became a mandatory obligation starting in 2016, and in 2017, the flexible Open Research Data Pilot (ORD) was

extended to all disciplines based on the principle of "open by default, closed when necessary" [27].

In response to the European Council's 2016 strategic goal of achieving default immediate open access to all peer-reviewed publications by 2020, the EU is taking two approaches: first, reducing dependence on publishers by establishing its own open research publishing platform (the OpenResearchEurope Publishing Platform, ORE) [37]. ORE provides a fast OA publishing channel for peer-reviewed articles and eligible preprints funded by Horizon 2020, offering grantees an optional, free, and fast third way beyond gold and green open access. Second, it is transforming toward a transparent, competitive European publishing market. Due to slow progress in open access, the EU released the radical open access S Plan in September 2018, indicating that some European funders will only provide funding for fully open access publications by 2020 [38]. The S Plan hopes to accelerate the transition to OA by establishing a strong alliance of research funders. The OA2020 Initiative recommends that all stakeholders in academic publishing work together to change the current publishing system, replacing subscription publishing models with new publishing models to ensure transparent publishing costs and economic sustainability. In coordination with OA2020, universities and libraries in several European countries (such as Germany, France, and Sweden) are negotiating with major publishers, hoping to reach new licensing agreements, improve journal pricing, and reduce institutional financial burdens.

2.2.2 Building Open Science Infrastructure The EU Commission's goals for open data and knowledge circulation require sustainable electronic infrastructure guarantees. Electronic infrastructure provides services for data preservation and reuse and is a key element of data-driven social research and innovation. Europe has established the European Strategy Forum on Research Infrastructures (ESFRI) and the e-Infrastructure Reflection Group (e-IRG) to support research infrastructure policy formulation and guide European electronic infrastructure development. Currently established electronic infrastructures include GEANT, EGI, PRACE, EUDAT, IDGF, OpenAIRE, and LIBER, but these infrastructures are not sufficiently interconnected, each being responsible for specific domains, requiring researchers to switch between different facilities and causing severe knowledge fragmentation.

In the "European Cloud Initiative—Building a Competitive Data and Knowledge Economy in Europe," the European Commission proposed developing the European Open Science Cloud (EOSC) into a trusted environment for storing, sharing, opening, and interconnecting data and services, achieving service integration across member states, at the European level, and internationally, and accelerating the transition to the Digital Single Market. The EOSC will bring together existing and emerging data infrastructures to create a trusted virtual environment for all European researchers to store, manage, analyze, and reuse data, enabling them to benefit from data-driven science. Data providers can

benefit from data annotation, storage, management, and long-term preservation services on trusted repositories, while data users will have the right to discover, access, reuse, combine, and analyze research data. Building the EOSC is a key step for Europe's transition to open science and full utilization of data-driven science. Overall, the EOSC will: strengthen the effective interconnection of existing research infrastructures for open science; enable access, sharing, and reuse of cross-disciplinary and pan-European research data; and enable data-intensive research in a secure virtual environment, ensuring researchers benefit from data-driven science.

2.2.3 Incentivizing Researchers to Practice Open Science The Amsterdam Call for Action on Open Science and many documents clearly state that supporting reward measures and evaluation systems are important conditions for transitioning to open science. As long as journal rankings and impact factors remain the main criteria for judging academic quality, merely opening outputs and infrastructure will have limited impact on researchers. Linking open practices to performance evaluation and improving current scientific evaluation indicators to incentivize researchers to publish articles and data through open access will enable researchers and citizens to more fully participate in the open science process. Multiple organizations across the EU have issued a series of policy measures to incentivize researchers' open behaviors, such as the Science in Transition organization, which proposed developing new research performance evaluation indicators in 2014 [39], and the Open Science Rewards Working Group, which released a report on research career evaluation in 2017, recommending full recognition of the value of open science practices in career assessments [40].

The EU has been exploring new evaluation indicators and incentive mechanisms. In 2015, the European Commission's Directorate-General for Research and Innovation established the Altmetrics and Open Science Working Group, which is currently developing open science indicators. These indicators will be discussed on the open science policy platform and will produce the "Bucharest Declaration" [41] to supplement the "San Francisco Declaration on Research Assessment" (DORA). OpenAIRE also enriches the research and career evaluation system by providing new-generation metrics that link scientific software publication and data to academic records as part of academic recognition, providing references for open evaluation.

2.2.4 Open Science Policy Platform Support The Open Science Policy Platform (OSPP), established in 2016, is a high-level advisory group that provides advice for European open science development. As a dynamic stakeholder-driven mechanism, it utilizes expert groups and external expertise to advise the Commission on how to further develop and implement open science policies [42]: supporting policy formulation: helping identify problems that need addressing and proposing recommended policy actions; supporting policy implementation: reviewing best practices, developing policy guidelines, and promoting

stakeholder adoption.

In 2018, the European Commission announced that the policy platform had identified eight priority development areas for European open science based on the European open science agenda and the Amsterdam Call for Action. The platform's framework structure and priority development areas are shown in Figure 1 [Figure 1: see original paper]. The open science policy platform will ensure the participation of all stakeholders in policy preparation, formulation, and implementation through bottom-up discussions and best practice analysis, and provide recommendations to the Commission on necessary policy actions, ensuring that open science can fulfill its potential. Stakeholder participation and evidence-based policy formulation can strengthen the connection between science and society while ensuring policy transparency and effectiveness.

2.2.5 Monitoring and Reporting Measures for Open Science Development All stakeholders, member states, and the European Commission have the responsibility to actively promote open science within their respective communities and regularly monitor and report progress publicly. For example, the EU requires the Open Science Policy Platform to report progress at least once every two years; each member state designates National Points of Reference (NPRs) to maintain long-term contact with the European Commission and report national open access progress. In addition, there are specific evaluation reports for particular fields.

To ensure all policy formulation is based on the latest information and practical evidence, the European Commission commissioned RAND Corporation to develop the Open Science Monitor to identify the main drivers, incentives, and constraints of open science development. The monitor collects relevant and immediate indicators on open science development in Europe and partner countries worldwide, providing data support for the European open science policy platform, policymakers, and stakeholders from three perspectives: open access to publications, open research data, and open scholarly communication.

2.2.6 Education, Training, and Other Support Services EU member states, universities, relevant institutions, and basic service platforms all provide consultation, training, and other services on open science. By conducting open science education and training, they improve researchers' open science awareness and help them learn how to open research processes and results. The European Commission funded the FOSTER and FOSTER Plus projects under the FP7 and Horizon 2020 work programs to provide training and resources to improve the skills needed for open science practice [44]. OpenAIRE Advance also provides standardized open science skills training for researchers, data practitioners, and citizen scientists [45]. Regarding talent, Horizon 2020's 2014-2017 work program funded the EDISON project to identify curricula and training standards to meet the growing demand for e-infrastructure and data professionals [46]. The 2016-2017 work program addressed data-related skills shortages

through training, supporting skills development for e-infrastructure providers and users, and supporting FAIR data management (such as OpenAIRE, RDA Europe, FREYA). These systematic activities cultivate a culture of data sharing and FAIR data management, helping to develop the human resources needed for open science operations.

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3. Implementation Results of European Open Science

3.1 Increased Open Access Participation

Currently, open access policies are not uniform among European countries. Different member states and stakeholders have different situations and needs, and no consensus has been reached on the appropriate path to immediate open access. The European Commission, member states, and stakeholders are jointly evaluating and determining how to formulate a balanced plan to achieve the goal of full open access before 2020. In 2018, 31 ERA countries had formulated policies and/or guidelines to support open access publications, research data management, or open science, with 19 countries having legal measures in these three areas, though enforcement varies significantly. Only a few ERA countries have taken measures to monitor the development and impact of OA and research data management (RDM) policies [47]. Although the transition to open science has begun, it is still hindered by issues such as copyright, costs, data privacy, insufficient OA training, lower quality of OA journals, and institutional policies that encourage publication in traditional journals.

3.2 Enhanced Interoperability and Standardized Management of Open Research Data

In terms of open research data, in addition to requiring openness as much as possible, the EU has also achieved great results in scientific data management, making datasets interoperable and maximizing reuse. Open research data interoperability has been enhanced, and management is moving toward unified standardization, namely data management following FAIR principles. The Horizon 2020 framework requires submitting FAIR Data Management Plans (DMPs) as an obligation for every grantee, representing a key element of good data management. Europe has begun taking action to support comprehensive adoption of FAIR data principles, such as releasing the FAIR Data Action Plan, establishing the FAIR Data Expert Group, and launching the GO-FAIR initiative. However, related RDM policies are often recently introduced and still require strengthened coordination among countries. The ongoing EU copyright reform points out the need to establish new EU-wide copyright exceptions for modern research methods of text and data mining, but limited to “research institutions” and “for scientific research purposes” [48], which has largely improved the reusability of research data.

3.3 European Open Science Cloud Construction Enters Substantial Progress Phase

Between 2016 and 2017, Europe conducted extensive research and consultation within the scientific community, confirming the need for the EOSC pan-European research data infrastructure to improve the current fragmented data situation and make data easy to store, find, share, and reuse. Subsequently, the European Commission released the EOSC Implementation Roadmap in March 2018 [49], dividing EOSC implementation into two phases. The initial phase is implemented through Horizon 2020 projects, including six action lines: EOSC architecture, FAIR data principles, services and datasets accessible through EOSC, participation rules, governance structure, continuing until the end of 2020; the second phase's start time depends on the European Commission and member states' in-depth evaluation of the initial phase. The year 2018 was a milestone year in EOSC development; the EOSC was officially launched in November, marking the end of years of consultation among EU stakeholders and the beginning of the implementation phase. The first phase has already produced initial results: the EOSC Portal provides access to data, services, and resources as a common entry point for EOSC services and data gateways. The governance architecture officially released in November is a multi-level, multi-institution, multi-stakeholder framework with clear institutional, administrative, and advisory roles that will evolve over time.

3.4 Rapid Development of Citizen Science

The European Commission funded the citizen science Socientize project and formulated the "White Paper on Citizen Science for Europe" [50] to ensure citizen science receives maximum recognition and exerts influence, exploring new methods for individual citizen participation in scientific processes. At the same time, citizen science has received support from the Collective Awareness Platforms for Sustainability and Social Innovation (CAPS), which aims to promote citizen science development based on an ICT open science framework, combining social media, distributed knowledge creation, and IoT data [51]. Europe also has a specialized non-profit association promoting citizen science—the European Citizen Science Association (ECSA)—composed of participants from over 28 countries in the EU and other regions, aiming to encourage the development of the citizen science movement in Europe and strengthen public participation in scientific processes, mainly by initiating and supporting citizen science projects and research on citizen science [52].

3.5 Reform of Evaluation and Reward/Incentive Mechanisms

The 2016 Amsterdam Call for Action on Open Science outlined two important strategies for supporting open science, one of which is establishing multiple evaluation, reward, and assessment systems suitable for science and society as a whole to produce and share knowledge [53]. The European Commission's Altmetrics Expert Group released the "Next-Generation Metrics: Responsible Metrics and

Evaluation for Open Science" report [41], developing next-generation metrics for open science (Next Generation Metrics for Open Science). Unlike traditional metrics that only consider research output quality, these consider all research outcomes and align with the open science system. Some European countries have already pilot-tested the use and feasibility of next-generation metrics in research (such as Austria, Finland, and Slovenia), and some organizations have integrated altmetrics into their repositories for research evaluation.

The strategy of incentivizing open practices also requires fundamental paradigm shifts in assessment, recruitment, and salary systems. This paradigm shift requires active collaborative participation from the main stakeholders in the research system—researchers, funders, and governments—in open science implementation. Transforming researchers' original competitive concepts and the current "publish or perish" culture, and ensuring they are rewarded for open science behaviors, is the focus of open science incentive work. However, overall, the "publish or perish" culture has not changed much, and the overall evaluation mechanism does not match the open science system, requiring more efforts.

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4. Implications of European Open Science Development for China

Reviewing the course of European open science development, it is evident that Europe's main motivation for promoting open science is to fully utilize data-driven economic development and activate innovation. China is currently implementing an innovation-driven development strategy, and open science has a positive driving effect on open innovation. Open access and open science development can save R&D costs for SMEs and significantly promote their development. However, compared with Europe and other developed countries and regions that have vigorously promoted open science development in recent years, China still lacks top-level policies, middle-level development systems, and bottom-level practical paths for promoting open science development, making its development somewhat weak. Therefore, there is an urgent need to learn from foreign advanced development experiences. When referencing and drawing on European open science development experience, China should focus on the following aspects.

4.1 Accelerate the Establishment and Improvement of an Open Science Development Policy System

EU-level, member state-level, and institutional-level policies form a vertical policy hierarchy, while policy agendas for training incentive mechanisms, eliminating obstacles, opening channels, promoting open access, and strengthening infrastructure construction form a horizontal policy hierarchy. The interweaving of vertical and horizontal policies creates a policy network, providing comprehensive support for European open science development. China lacks top-level

policy guidance for open science and has not yet issued national policy guidelines, and researchers at all levels of the scientific system, research institutions, and scientific personnel do not have deep enough understanding of the strategic significance, importance, and trends of open science. It is recommended that China learn from EU policy formulation experience by first conducting open science research and expert consultation in China, widely soliciting opinions and suggestions, then setting stage goals, and accelerating the establishment and improvement of a vertical policy system for promoting open science development at the national, provincial/municipal or departmental, and institutional levels, and accelerating the improvement of horizontal policy systems formed by policy agendas such as open channels and infrastructure that support open science development. The interweaving of vertical and horizontal policies will form a supporting policy system for China's open science development.

4.2 Establish a Complete Development System

From basically promoting open access to scientific publications to further promoting research data reuse, and then to the next-generation evaluation system intended to improve the entire research culture, the EU has specialized committees to coordinate and promote open science development, building a complete open science development system that makes open science development rational, comprehensive, and progressive. China's investment in and promotion of open science are mostly scattered actions, such as joining the OA2020 initiative and promoting scientific data standard management, but open science involves many aspects, and merely introducing measures for certain points without overall planning and specific charters leads to weak follow-up actions and poor driving effects on open science development. China should fully recognize that open science is a more efficient way of doing science, and the transformation of scientific methods cannot be achieved overnight. There should be a complete promotion system with implementable stage goals and action plans. Combine soft and hard approaches, financial support with cultural change, considering both the hard change needs of open science, such as open science infrastructure construction, research paper open access, research data sharing and reuse standards, and fully considering the institutions, personnel, and supporting facilities involved; on the other hand, consider the cultivation of open science culture, improving evaluation systems, establishing knowledge alliances, inviting enterprises and universities to participate in various activities, strengthening the relationship between science and society, improving knowledge transfer and transformation efficiency, and expanding the utilization benefits of public funds.

4.3 Follow a Pragmatic Practical Path in Specific Practices

Regarding scientific publications, Europe has set a goal of full open access by 2020 and has taken measures such as building an open publishing platform and introducing fund policies to pressure publishers. Regarding research data reuse, it has vigorously promoted the adoption of unified FAIR data processing princi-

ples to make data interoperable across electronic infrastructures and knowledge repository platforms. Regarding incentivizing researchers' open science behaviors, it has improved evaluation indicators and formulated supporting incentive and reward mechanisms.

China lacks clear open access goals, unified data processing standards, and corresponding evaluation indicators, resulting in slow open access progress, severe data heterogeneity among institutional repositories, and low researcher enthusiasm. Therefore, at the strategic level, open science should be embedded in social development as a socio-economic driver, with clear goals supporting open access and open science development, and joint open science programs should be implemented. At the practical level, general infrastructure guaranteeing scientific development should be built, effective interconnection of existing open science infrastructure should be strengthened, such as connecting the China Science and Technology Cloud, China Open Research Knowledge Cloud, and Chinese Academy of Sciences Data Cloud, to achieve cross-disciplinary research data access, sharing, and reuse, and to coordinate and improve the interoperability of national-level scientific data research infrastructure. In terms of scientific data, merely issuing hard data management measures is insufficient; long-term plans for preserving research data and results should be formulated, supporting common interfaces, data standards, and software development, and building China's own influential data storage centers. Promoting data reuse and sharing among various scientific research knowledge systems is necessary to avoid the siphoning effect from developed countries on China. At the same time, scientific evaluation indicators should be improved, and incentive and reward mechanisms encouraging open science practices should be formulated to fully mobilize researchers' collaborative enthusiasm and ensure substantive progress in China's open access and open science.

4.4 Provide Stable and Systematic Auxiliary Support

EU research project funds allow for 5% data management funding [54], and stable financial support has greatly promoted European open science development. For China, stable financial funding remains an important factor constraining open science development. Since China currently lacks systematic scientific plans to promote open science development, although many research funding agencies support payment of open access article processing charges with project funds, the intensity, breadth, and continuity of financial support are far from meeting practical needs. Therefore, under the situation where China's open science development clearly lags behind Europe and other developed countries and regions, national and provincial-level science and technology management departments should fully recognize the great prospects of open science, increase concentrated investment and promotion in open science, clearly define the proportion of funds for open science-related projects in relevant policies, rather than just one-time appropriations in the form of projects. Second, learn from EU open science training practices, carry out open science skills training to

address researchers' low relevant skills and insufficient professional support. Finally, learn from the EU open science development monitoring mechanism and establish relevant reporting and monitoring systems for China's development.

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