Research on the Open Innovation Connotation and Ecological Mechanism of Open Science

Authors: Chen Xuefei, Huang Jinxia, Wang Fang, Xuefei Chen

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Abstract

Purpose/Significance Open science is emerging as a driving force for innovation. This study aims to analyze the connotational consistency between open science and open innovation, investigate the dynamic mechanism through which open science influences the innovation ecosystem, and provide references for research on open science innovation ecosystems and for implementing open science governance oriented toward scientific and technological innovation. Methods/Process An analytical framework for the connotation of open science is established based on the "resources-process-actors-behaviors" structure, which serves as the theoretical framework to analyze the open innovation connotation of open science. The mechanism of open science' s impact on the innovation ecosystem is examined from the perspective of the innovation process. Results/Conclusion The open science innovation ecosystem has already formed, and the connotations of open science and open innovation demonstrate consistency. Open science plays a role across different stages of innovation, with explicit and tacit knowledge flowing openly throughout various innovation phases, thereby accelerating open science innovation, open innovation, public innovation, and responsible innovation.

Full Text

A Study on the Connotation of Open Innovation in Open Science and Its Ecological Mechanism of Action

Authors: Chen Xuefei[1], Huang Jinxia[12], Wang Fang[1]

[1]National Science Library, Chinese Academy of Sciences, Beijing 100190, China
[2]Department of Library, Information and Archives Management, School of Economics and Management, University of Chinese Academy of Sciences, Beijing 100190, China

Abstract

Purpose/Significance: Open science is becoming a driving force for innovation. This paper aims to analyze the consistency between the connotations of open science and open innovation, investigate the dynamic mechanism through which open science influences the innovation ecosystem, and provide a reference for research on open science innovation ecosystems and for developing open science governance oriented toward scientific and technological innovation. **Method/Process**: We establish an analytical framework for open science based on "resources-process-subjects-behavior," and use this theoretical framework to analyze the open innovation connotation of open science. We then examine the mechanism through which open science acts upon the innovation ecosystem from the perspective of the innovation process. **Results/Conclusion**: An open science innovation ecosystem has already formed, and open science and open innovation demonstrate connotative consistency. Open science plays a role at different stages of innovation, with explicit and tacit knowledge flowing openly across various innovation phases, thereby accelerating open science innovation, open innovation, public innovation, and responsible innovation. The limitation of this paper is that the relevant research remains at the theoretical level. For instance, the open science spectrum needs to be refined to an assessable and operational granularity, and the mechanism of open science' s impact on the innovation ecosystem requires more case studies for validation. Simultaneously, based on this research, we need to further explore the governance mechanisms of open science under the innovation system and the linkage strategies among science, industry, society, and policy under the open innovation ecosystem.

Keywords: Open innovation, Open science, Innovation ecology, Open sharing

1 Introduction

In the context of globalization, society is shifting from closed to open innovation, with open science emerging as a new trend in the transformation of international scientific research paradigms and scientific organization. In 2013, European Commission Vice President Neelie Kroes stated that "we are entering the era of open science." On October 15, 2015, the OECD released the report *Making Open Science a Reality*, arguing that science is increasingly data-driven, online storage has made accessing and utilizing research information possible, and these developments have accelerated knowledge transfer among researchers and across fields, leading to the rapid development of "open science."

Open science has become a global consensus and call to action. Numerous initiatives have been launched internationally, including the Budapest Open Access Initiative, the Amsterdam Call for Action on Open Science, the Open Access 2020 Initiative, Plan S, and the Beijing Declaration on Research Data. The OECD issued the *OECD Principles and Guidelines for Access to Research Data from Public Funding* in 2007 to explore open research methods, processes,

and practices. The Food and Agriculture Organization of the United Nations released the *Global Roadmap for Open Science Hardware* (2018), and UNESCO advocates using open science to promote global cooperation and address global challenges. In November 2021, UNESCO launched the global "Recommendation on Open Science" to guide member states in formulating national open science strategies at the policy level, thereby enhancing national innovation capabilities and promoting socio-economic development.

At the national level, in August 2022, the White House Office of Science and Technology Policy (OSTP) released new policy guidelines requiring all research papers funded by the federal government to be made immediately and freely available to the public. The European Union released the *European Open Science Cloud* (2019), the Netherlands formulated the *National Plan for Open Science* (2014), Japan established the Open Science Committee (2017), and other countries including the United Kingdom, Canada, Australia, and various African nations have also developed national open science policies and built open science ecosystem systems. The EU invested €600 million in 2016 to launch the construction of the European Open Science Cloud (EOSC), aimed at building an information infrastructure serving 1.7 million researchers and 70 million scientific and technological professionals in Europe. The "Horizon Europe" program (2021-2027) allocated a budget of €25.8 billion for open science alone, while the U.S. NSF also invested $8 billion in open data. At the end of 2021, open science was written into the *Law of the People' s Republic of China on Science and Technology Progress* for the first time.

Open science is shaping a new academic innovation ecology. The European Commission' s 2016 report *Open Innovation, Open Science, Open to the World* pointed out that the concept of open science reflects a paradigm shift in scientific research over the past 50 years: whereas the previous standard practice was to publish research results in scientific publications, the current trend is to share and utilize all available knowledge at the early stages of the research process. The deepening of the open science movement has expanded from the single principle of open access to principles of transparency, reusability, inclusiveness, participation, and accountability, extending from open publications to the sharing of data, code, and other research products, the sharing of research processes, and citizen science. The open science practices adopted during the global COVID-19 pandemic that began at the end of 2019 effectively supported global vaccine and drug research, further convincing the global scientific community that open science represents a new future research paradigm that accelerates scientific research.

Compared with early open access and open data movements that focused on the free access to research outputs (papers or data), open science places greater emphasis on the open exchange and application of knowledge and highlights open and collaborative research methods, thereby accelerating the scientific innovation process and promoting scientific development. Under this paradigm, open sharing has become a new social culture, data has become a new produc-

tion factor, and collaborative research has become an innovation mechanism. Global research institutions and their stakeholders are moving toward a new open science innovation ecosystem. Open science is becoming a driving force for innovation, with both sharing common key objectives and internal operational logic.

Therefore, this paper focuses on the connotation of open innovation under open science and its ecological mechanism of action. We construct an analytical framework for the connotation of open science, use this framework to analyze the connotative consistency between open science and open innovation, and examine the mechanism through which open science influences the innovation ecosystem from the perspective of the innovation process. This provides a theoretical basis for research on open innovation ecosystems and open science governance.

2.1 Analytical Framework for the Connotation of Open Science

Different scholars and stakeholders have interpreted open science from various perspectives. However, due to the complexity, broad scope, unclear boundaries, and diverse schools of thought surrounding open science, there is currently no unified standard definition.

Ruben conducted a systematic literature review and categorized the concept of open science into four types: open science as knowledge, open science as transparent knowledge, open science as accessible knowledge, and open science as collaboratively developed knowledge. Based on this, he established a comprehensive and rigorous contemporary definition: open science is transparent and accessible knowledge that is shared and developed through collaborative networks. The most widely recognized definition is UNESCO' s *Recommendation on Open Science*, which defines open science as an inclusive construct that combines various movements and practices aimed at making scientific knowledge publicly accessible, available, and reusable for all, promoting scientific collaboration and information sharing for the benefit of science and society, and opening the processes of creating, evaluating, and disseminating scientific knowledge to social actors beyond traditional scientific communities. Open science encompasses all scientific disciplines and aspects of academic practice, including basic and applied sciences, natural and social sciences, and humanities, and is built upon the following main pillars: open scientific knowledge (scientific publications, open data, open-source code and software, open hardware), open science infrastructure, open science communication, open participation of social actors, and open dialogue with other knowledge systems.

Open science has already transformed the entire research ecosystem, establishing a research scenario that enables funding agencies, research institutions, information service organizations, the public, and other relevant stakeholders to collaborate in research activities across various barriers, with research outputs, processes, and facilities being accessible, understandable, evaluable, and

reusable. In this scenario, the elements contained in open science continue to evolve dynamically, and its scope continues to extend, while its principles become increasingly clear.

Based on the deconstruction of existing open science connotations, this paper establishes an analytical framework for open science based on "resources-process-subjects-behavior." Accordingly, we propose four key components of open science: "open scientific knowledge resources-research process-participating subjects-research behavior." Drawing on Vicente-Sáez and Martínez-Fuentes' theory of the three pillars of open science (accessibility, transparency, and participation), we further specify these components into four principles of open science: the principle of openness of scientific knowledge, the principle of transparency of the research process, the principle of inclusiveness of participating subjects, and the principle of collaboration in research behavior.

1. **Openness of Scientific Knowledge**: All knowledge generated throughout the scientific lifecycle and the platforms that carry this knowledge are openly shared and accessible, including open access resources, open lab notebooks, open data, preprints, open code, open software, open educational resources, open hardware, and open knowledge infrastructure. However, scientific knowledge is shared under specific open licenses, with legal protection and intellectual property recognition. Open science does not mean "free."

2. **Transparency of the Research Process**: The entire research process must be transparent. Before research, studies can be registered through pre-registration and registered reports. During experiments, open experiments and open notebooks can be conducted, with detailed records of scientific experimental data and related information on methods, conditions, technical requirements, and application conditions to facilitate reproducible research by others. After results are published, open peer review and open review reports can be implemented. A transparent research process can promote responsible research among scientists, making open science an intrinsic "trust mechanism" for academic exchange.

3. **Inclusiveness of Participating Subjects**: This inclusiveness is first reflected in the identity of participants. It encompasses both cross-disciplinary, cross-institutional, and cross-regional collaboration within the scientific research system and the joint participation of the scientific research system with different stakeholders or even non-scientific research systems. Subject organizations can include academic societies, research and education institutions, the public, governments, NGOs, technology R&D communities, R&D enterprises, publishing institutions, information service organizations, research funding agencies, etc. For individuals, participation is open regardless of nationality, race, gender, language, age, discipline, socio-economic background, or career stage. Second, it is reflected in the inclusiveness of participation levels. Any subject can assume any competent role in the scientific research process; for

example, a scientific project can be initiated and designed by non-research personnel.

4. **Collaboration in Scientific Behavior**: Open science is a collaborative, knowledge-division-based organizational approach to research work. Currently, many major scientific infrastructures are shared globally, and the construction of multi-center open collaboration projects and platforms has become an important measure for attracting and consolidating innovation achievements and enhancing global scientific influence. For example, China' s space station invites countries worldwide to conduct experiments inside and outside the cabin. The lunar farside exploration data obtained by Chang' e-4 is open to the world, and major Chinese research infrastructures such as the Five-hundred-meter Aperture Spherical Telescope (FAST) and the Experimental Advanced Superconducting Tokamak (EAST) have become world-class platforms for scientific research collaboration.

[Figure 1: see original paper]

2.2 Open Innovation Under the Open Science Connotation Framework

(1) The Relationship Between Open Science and Innovation

Open science is both a scientific organization mechanism and a knowledge production mechanism for participating in scientific and technological innovation. Paul David argues that the past success of our innovation system can be attributed to the combination of its proprietary and open science models, maintaining an appropriate balance. Open science excels at generating new knowledge, while proprietary science (knowledge based on patent protection) is stronger at transforming existing knowledge reserves into innovation. However, innovation systems are becoming increasingly inefficient, with the cost of research and innovation not only increasing but growing exponentially. The main reasons are the increasing complexity and expense of science, misaligned incentive mechanisms, and the Balkanization of knowledge caused by proprietary science. Many scholars have explored theories and practices for improving scientific and technological innovation systems through open science. For example, E. Richard Gold proposed that Open Science Partnerships (OSP) are a mechanism to reverse the declining efficiency of scientific and technological innovation systems. Ruben Vicente-Saez proposed that the openness of innovation is being reshaped by open science practices, which have tremendous potential to accelerate research and innovation processes to find solutions to major social challenges and to cultivate highly innovative and entrepreneurial talent. The European Commission has positioned open innovation and open science as the two main pillars of its research agenda. The German think tank Stifterverband connects open innovation and open science through a "strategic openness" policy framework, enabling enterprises to increase their innovation output

and enhance public trust in science. Beck et al. consider openness as the glue between innovation and science and propose "open innovation in a scientific research framework." The role of open science in vaccine development during the COVID-19 pandemic also demonstrates how open science has transformed the innovation ecosystem. Domestic scholars have also explored the intrinsic connections between the open science paradigm and scientific and technological innovation from perspectives including new institutional economics, innovation economics, constructivist theory, open innovation, and responsible innovation.

From the above research, it is evident that open science and open innovation are closely connected, often occurring simultaneously within ecosystems and influencing each other.

(2) The Open Innovation Connotation of Open Science

In an open science innovation ecosystem, the role of open science lies in reducing data and material costs in the research process, improving the quality and efficiency of scientific endeavors, and generating high-quality research. The role of open innovation lies in reducing the transaction costs of innovative knowledge outputs, improving the efficiency of innovation activities, and shortening the transformation cycle. Open science aims to achieve open scientific results, promote the formation of innovative research and cooperative relationships, and facilitate the transformation of knowledge into socio-economic value. The essence of open innovation is the free flow of innovative knowledge resources across organizational boundaries, with various innovation subjects forming efficient collaborative relationships through open innovation activities, promoting the flow of innovative knowledge resources in collaboration, and ultimately achieving value creation and win-win outcomes. To provide a theoretical basis for the consistency between the two, this paper proposes that open innovation has four key components based on the "resources-process-subjects-behavior" analytical framework of open science: innovative knowledge resources, innovation process, innovation subjects, and innovation activities.

Transparent and Open Innovation Knowledge Resources and Innovation Process: The essence of innovation is the utilization of knowledge resources, and the accelerated flow of knowledge resources drives innovation. The general definition of open innovation is "the use of purposive inflows and outflows of knowledge to accelerate internal innovation and expand the markets for external use of innovation." Laursen et al. further propose that an important prerequisite for achieving full utilization of innovation resources is the free flow of knowledge and information, where inward-facing innovation involves using external knowledge for innovation, and outward-facing innovation involves the spillover of internal knowledge to support innovation in other institutions. Thus, the core of open innovation emphasizes the interaction of innovative knowledge resources between heterogeneous internal and external subjects, making the innovation process more transparent. Whittington proposed that implementing open strategies in the technological innovation process requires attention to the

visibility of innovation content and process.

The basic premise of open innovation is to open the innovation process to all active participants so that knowledge can circulate and be shared more freely and be transformed into products and services that create new markets. Therefore, open innovation emphasizes "open sharing of innovative knowledge and processes," which is precisely the interpretation and extension of the principles of openness and transparency of open science within the innovation system.

Value Co-creation Based on the Inclusiveness of Innovation Subjects: Under the open innovation paradigm, innovation subjects are more diverse and inclusive, with multiple actors jointly participating in organizational innovation strategic dialogues, such as information exchange and value shaping. Cooperation among innovation subjects can be resource-based, such as cooperation based on market resources, professional resources, or institutional resources; it can be science-based or organization-based. The identity of subjects is also more inclusive, including suppliers, users, universities or R&D laboratories, competitors, consultants, enterprises in other industries, innovation intermediaries, etc. Taking the EU' s SWAFS (Science with and for Society) program as an example, it advocates for researchers, policymakers, citizens, universities, research institutions, educational organizations, industry associations, NGOs, and civil society groups to participate in the early process of transforming scientific research results into technological innovation.

From the key elements of the Open Innovation 2.0 concept, a specific innovation is no longer seen as the result of a predetermined and isolated innovation activity but as the result of a complex co-creation process. Invention becomes innovation only when users and the public become part of the value creation process, and creating a well-functioning ecosystem that allows for co-creation is crucial for open innovation. Therefore, "co-creation" is one of the criteria for elevating invention to innovation, and the principles of collaboration and inclusiveness in open science correspond precisely to the "co-creation" standard of open innovation.

(3) The Synergy Between Open Science and Open Innovation

Open science and open innovation share consistent connotative attributes. The higher the degree of openness, transparency, inclusiveness, and collaboration in scientific research, the higher the degree of open science, and under otherwise equal conditions, the stronger the open innovation capability. Based on the connotations of open science and open innovation, this paper maps the principles of openness and transparency of open science to the knowledge sharing principle of open innovation, and maps the principles of collaboration and inclusiveness to the value co-creation principle of open innovation. Simultaneously, drawing on the "Open Access Spectrum" guidelines for evaluating openness launched by PLOS and other institutions during the 2012 Open Access Week, we propose the concept of the "Open Science Spectrum," which divides the degree of open

science into four levels. Level 1 represents the lowest degree of open science, where open science is less developed, and levels of knowledge sharing and value co-creation are low, resulting in weak open innovation capability. As the level increases, the degree of open science increases progressively, and the support of open science for open innovation becomes stronger, and open innovation capability also increases. Level 4 represents the highest degree of open science, where open science is highly mature, levels of knowledge sharing and value co-creation are high, and the boundaries between research and innovation become increasingly blurred.

3 The Intrinsic Mechanism of Open Science' s Impact on the Innovation Ecosystem

Drawing on knowledge governance theory, this paper analyzes the dynamic mechanism through which open science influences the innovation ecosystem at different innovation stages from the perspective of the innovation process.

[Figure 2: see original paper]

3.1 The Open Science Mechanism in the Scientific Research Stage

Scientific innovation relies on the accumulation of prior knowledge. Zhang Xuewen et al. demonstrated from an institutional construction perspective that the institutional logic of cumulative innovation constructs the open science institution. Even for discrete innovation, the proprietary nature of knowledge can hinder subsequent innovation by reducing operational freedom.

In the scientific research stage, open science acts on the innovation system through knowledge sharing and open science innovation partnerships. Knowledge sharing primarily involves the flow of explicit knowledge. Scientific research teams can use open science knowledge outputs to develop new products or conduct service innovation, or they can spill over knowledge outputs through open science infrastructure to support external innovation. Open science shares knowledge, materials, and tools, avoids knowledge silos, accelerates research verification, and reduces innovation duplication, shaping a knowledge-sharing incentive mechanism based on priority and reputation, thereby improving the current scientific innovation system. However, knowledge sharing does not directly affect innovation productivity but rather serves more as a reserve of "raw materials."

Open science innovation partnerships primarily involve the flow of tacit knowledge. Through team diversification and tacit knowledge flow, they address the increasing complexity of science, effectively improving scientific research efficiency and reducing research costs. They enable breakthrough innovation through the combination of knowledge and skills and aligned incentive measures. Open science can also enhance the robustness of the innovation system, achieving higher-quality results through public verification by external experts.

A typical example of open science innovation partnerships is cross-disciplinary or multi-center distributed collaboration. For instance, the development of anti-leukemia drugs through collaboration between the Structural Genomics Consortium and the Ontario Institute for Cancer Research resulted in the largest preclinical drug deal in Canadian history and shortened the development timeline by two years compared to expectations.

3.2 The Open Innovation Mechanism in the Technology R&D Stage

Compared with open science, open innovation faces the technology development stage and is generally considered to utilize purposive knowledge exchange to accelerate internal innovation and expand external innovation. From the previous connotational relationship, it is clear that both open science and open innovation accelerate certain processes through knowledge sharing, and the inflow of knowledge from scientific discoveries can also trigger innovation. Therefore, open science can lead to open innovation. Vicente-Sáez and Martínez-Fuentes argue that "open science is transparent, accessible knowledge that can stimulate business strategies, actions, and practices. In other words, new forms of collaboration help break down the barriers between open science and open innovation." In addition to academic institutions, some R&D-led enterprises also participate in open science. For example, Siemens, IBM, and Tesla openly publish numerous research results instead of patenting them. Zhang Xuewen et al. analyzed Allergan' s open science R&D model and concluded that the open science R&D model represents a unique innovative mindset and, more importantly, a strategic choice for the future that emphasizes crowdsourcing and collaboration in R&D.

According to the definition of open innovation, at this stage, open science primarily supports innovation within enterprises through knowledge accessibility and enables enterprises to share knowledge externally to support external innovation. Scientific research creates new theories and knowledge, with explicit knowledge including journal papers, books, conference resources, experimental data, software, and code. Under the open science model, this explicit knowledge more openly spills over to industry, supporting industry utilization and transformation into innovative outcomes. On the other hand, enterprises are opening up their original patented knowledge to spill over to academic research. A current trend is enterprises donating patents to research institutions while retaining the right to freely license the patents within their business scope, allowing research institutions to apply the patented knowledge to the combination of academic and applied research to achieve cross-industry innovation. For example, Pennsylvania State University and Virginia Tech donated patents worth $64 million, and Kellogg Company donated patents worth $49 million to Michigan State University.

The open flow of tacit knowledge is primarily formed through research outsourcing/crowdsourcing services and partnerships. The most important attribute of open innovation is collaboration. The rise of open science has changed enter-

prises' R&D models, with enterprises placing greater emphasis on R&D cooperation with academic institutions and other industrial partners, thereby helping enterprises integrate excellent innovation capabilities to achieve innovation efficiency improvements. To accommodate open innovation, some academic research institutions have also formed cooperation networks that provide solutions for industrial technology, such as the RFID Global Academic Research Lab Network composed of seven renowned global research institutions, which achieves the integration of global R&D capabilities for technological innovation and application. Additionally, outsourcing research activities provides new possibilities for small and medium-sized enterprises (SMEs) to overcome "small responsibilities." Under the open science R&D model, SMEs that could not previously conduct basic research on their own can also outsource scientific questions to research institutions, thereby enhancing innovation competitiveness. Large enterprises 剥离外包非核心价值链研发给研究机构，也有效降低了研发成本和避免了重复研究。开放科学的研发模式将更加快速发现和聚拢创新资源，不断优化创新生态。

3.3 The Citizen Science Mechanism in the Social Inclusion Stage

Crowdfunding websites enable citizens to fund research they are interested in, and citizen science platforms encourage everyone to share their time and expertise to help solve challenges. Therefore, citizens and professionals previously excluded from the innovation system have become important participants in the innovation system. Citizen science is often more open not only in terms of participation but also in terms of transparency of the research process and disclosure of intermediate results and data compared to traditional projects. The greatest advantage of citizen science is its ability to utilize a large contributor base and use crowdsourcing techniques to organize scientific projects, generating new knowledge in specific fields.

The main innovation models of citizen science include four project types:

1. **Citizen Contribution Projects**: In these projects, citizens are contributors who assist scientists in collecting and analyzing data. Citizens contribute data or resources through open science platforms, or academic institutions provide citizen scientists with shared access to laboratory instruments. For example, the online platform Zooniverse currently hosts over 80 research projects in natural sciences, medical sciences, and humanities, with more than 2.2 million volunteers. Projects are led by professional scientists, and the public helps generate and analyze data by classifying or transcribing images, sound, and video files. The project has achieved many significant discoveries.

2. **Citizen Collaborative Science Projects**: These projects are jointly driven by scientists and public members, with citizens not only contributing data but also participating in project design, analysis, dissemination, and discovery processes. For example, the Epidemium online platform brings together cancer scientists and citizen members of data science to

advance cancer research using big data.

3. **Co-initiated Science Projects**: These are projects initiated and conducted throughout the entire research process by the public and scientists, or even by the public alone. For example, the OpenCovid19 initiative launched by JOGL allows anyone to initiate, fund, recruit contributors, and conduct research. As of April 2021, the initiative had launched 123 projects in areas including tracking and predicting COVID-19 spread, researching the socio-economic and environmental consequences of the pandemic, developing diagnostic tests, and investigating potential COVID-19 treatments.
4. **Public Open Supervision Projects**: In the later stages of the scientific research process, the public supervises the potential social impact and ethical norms of projects and participates in dissemination, organizing debates, and replication studies.

3.4 The Responsible Innovation Mechanism Covering the Entire Innovation Process

Responsible innovation requires adopting an open science governance model throughout the entire innovation activity process to ensure compliance with research and social ethics norms. "Openness" is regarded as an important governance norm for responsible innovation oriented toward research and innovation activities, advocating for dynamic interaction between science, innovation, and society, multi-stakeholder inclusion, process responsiveness, and transparency, which are also the core values of open science. Mei Liang et al. constructed a framework for the open mechanism of responsible governance of scientific and technological innovation from the perspective of responsible innovation, covering the entire process of scientific research, technology development, and social development. Open science makes the research process transparent and open, alleviating the reproducibility crisis in scientific research. It incorporates multiple stakeholders in broader collaboration to manage technological risks and achieve economic value, and adopts public governance methods to ensure social benefits and norms.

Open science is no longer limited to knowledge sharing and accessibility but places greater emphasis on open science innovation practices. An open science innovation ecosystem is forming. This paper proposes an open science connotation framework and open science spectrum with four dimensions—openness, transparency, collaboration, and inclusiveness—and further analyzes the connotational relationship between open science and open innovation, as well as the dynamic mechanism through which open science influences the innovation ecosystem. The limitation of this paper is that the relevant research remains at the theoretical level. For example, the open science spectrum needs to be refined to an assessable and operational granularity, and the mechanism through which open science influences the innovation ecosystem also requires more case

studies for validation. Simultaneously, based on this research, we need to further explore the governance mechanisms of open science under the innovation system and the linkage strategies among science, industry, society, and policy under the open innovation ecosystem.

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