Assurance Mechanisms for Reproducibility of Research Outputs from the Perspective of Academic Publishing

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Abstract

Objective: Reproducibility is one of the fundamental principles of scientific research. This study proposes safeguard mechanisms from the perspective of academic publishing to address the increasingly serious reproducibility crisis in academia.

Methods: We investigated the relevant policies, guidelines, and practices of scientific journal publishers, academic societies, and international organizations, and systematically reviewed their reproducibility assurance measures for research data, research process, research results, and research types from two dimensions: publishing process and publishing orientation.

Results: In the publishing process dimension, it is necessary to formulate journal data policies, advocate for structured reporting, promote open peer review, and innovate detection technologies to ensure the transparency and reliability of research data and processes; in the publishing orientation dimension, it is essential to advance new article types such as Registered Reports and replication studies, and to strengthen editors' reproducibility awareness training.

Conclusion: To improve the reproducibility of China's scientific research outputs, it is necessary to draw on mature international experiences to accelerate the deposition of article-associated data, focus on cutting-edge initiatives in the field to promote innovation in academic publishing models, and refine the S&T evaluation system to facilitate the transformation of research concepts.

Full Text

Research on Mechanisms to Ensure the Reproducibility of Scientific Research Outputs from the Perspective of Academic Publishing

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Abstract

[**Purposes**] Reproducibility is one of the fundamental principles of scientific research. This paper proposes safeguard mechanisms from the perspective of academic publishing to address the increasingly serious reproducibility crisis in academia.

[**Methods**] We investigated relevant policies, guidelines, and practices from scientific journal publishers, academic associations, and international organizations, and systematically examined reproducibility assurance measures for research data, research processes, research results, and research types from two dimensions: publishing workflow and publishing orientation.

[**Findings**] In the publishing workflow dimension, it is necessary to implement journal data policies, advocate for structured reporting, promote open peer review, and innovate detection technologies to ensure the transparency and reliability of research data and processes. In the publishing orientation dimension, it is essential to promote new article types such as Registered Reports and reproducibility studies, while strengthening editors' awareness and training on reproducibility issues.

[**Conclusions**] To improve the reproducibility of China's scientific research outputs, we need to accelerate the deposition of research data associated with publications by drawing on international best practices, pay attention to cutting-edge initiatives in the industry to promote innovation in academic publishing models, and improve the scientific and technological evaluation system to foster a transformation in research concepts.

Keywords: Reproducibility; academic publishing; open science; reproducibility crisis; research integrity

[**Author Contribution Statement**]:
CHEN Xuwen: Data collection, paper writing;
YAO Changqing: Proposed research direction, finalized manuscript;
LEI Xue: Designed research framework, revised paper.

Reproducibility is a fundamental requirement of scientific experiments and a critical criterion for assessing the reliability of research findings. The scientific

community is currently facing a reproducibility crisis. In 2012, Begley et al. [1] found that only 11% of findings in cancer research could be replicated. In 2015, the Open Science Collaboration (OSC) [2] attempted to reproduce 100 studies published in top psychology journals and found that only 36% of the experimental results could be replicated. As open science continues to develop, the reproducibility crisis has attracted increasing attention from multiple stakeholders. Both the definition of open science proposed by the U.S. Office of Science and Technology Policy (OSTP) and the National Science and Technology Council (NSTC) [3], and NASA's Open-Source Science Initiative [4] list reproducibility as one of the principles and goals of open science.

Academic publishing constitutes a vital component of scholarly communication, and publishing institutions serve as important responsible parties for ensuring the reproducibility of research outputs. In 2016, Nature conducted a brief online survey of 1,576 researchers regarding research reproducibility [5]. Approximately 90% of respondents believed that a reproducibility crisis exists in science, while about 80% felt that funding agencies and publishers should take more measures to improve the reproducibility of research findings. In 2015, the Center for Open Science (COS) launched the Transparency and Openness Promotion (TOP) Guidelines, which have become the overarching principle for the academic publishing community to address reproducibility issues and have been endorsed by 86 journals, including *Science* and the *American Economic Association*. Based on the TOP Guidelines, publishing institutions have implemented a series of innovative practices to safeguard the reproducibility of scientific research.

Compared to the international emphasis on safeguarding research reproducibility, current domestic research on countermeasures for the reproducibility crisis remains superficial, primarily focusing on analyzing its causes and future research directions. For instance, Liu Chuanjun [6] discussed future research directions for the reproducibility crisis based on different psychological theories, while Wang Yang [7] examined the feasibility of implementing novel editorial systems to reduce irreproducibility in scientific papers from the perspective of science studies. However, there is limited research on how academic publishing institutions can play a role and what measures they should adopt to address the reproducibility crisis.

Therefore, against the backdrop of open science and from the perspective of academic publishing, this paper takes the TOP Guidelines as the main framework to systematically investigate and analyze policies, guidelines, and practices related to reproducibility assurance issued or implemented by major stakeholders, including scientific journal publishers such as Elsevier, Springer Nature, and Wiley, academic associations like the American Economic Association (AEA), and international organizations such as the International Committee of Medical Journal Editors (ICMJE). By comparing these international efforts with the current deficiencies in China, this study aims to provide reference points for domestic publishing institutions to address the reproducibility crisis.

1.2 Causes of the Reproducibility Crisis

The Retraction Watch database categorizes reasons for paper retractions into 102 types, 27 of which lead to irreproducible results. Among these, 15 types stem from experimental errors, while 12 involve intentional data fabrication or falsification by authors—representing research integrity issues.

The increasing complexity of scientific research may also contribute to the reproducibility crisis. From the experimental process perspective, scientific research is becoming more complex and systematic, making it difficult for researchers to fully and accurately control objective conditions such as experimental materials and equipment, leading to errors and irreproducibility. Additionally, social interactions among scientists in practice introduce new challenges to reproducibility; for example, large teams and centralized collaborative groups tend to produce research with lower reproducibility [10].

The evaluation system and incentive mechanisms for research outputs can also create reproducibility issues related to research integrity. High-quality journals represent a scarce resource for researchers. In a highly competitive environment, authors often pursue experimental results that strictly conform to their hypotheses to maximize publication opportunities. This leads to publication bias, where positive findings or studies with larger sample sizes are more likely to be published than negative results or small-sample studies. It may also cause authors to unconsciously select data and formulate hypotheses after seeing the results to cater to editors' preference for narrative storytelling—a practice known as HARKING (Hypothesizing After the Results are Known). Furthermore, in the current prevalent research evaluation system, publications serve as a key metric for assessing research capability and performance. Consequently, the pressure on researchers to publish constitutes another contributing factor to the reproducibility crisis.

1.3 Significance of Ensuring Reproducibility

(1) **Foundation for ensuring the healthy development of scientific research.** The Marxist view of science holds that the premise of science is dialectical materialism—that science cannot be separated from the laws of the objective world, and its object of observation is "a universal law of development." Reproducibility is a fundamental principle of natural science research and a reflection of the objective regularity of nature. Only by safeguarding reproducibility can we seek truth from facts, restore the true nature of scientific research, and ensure its healthy development.

(2) **Important measure for advancing research integrity construction.** In recent years, academic misconduct incidents have occurred frequently, and China has attached great importance to research integrity governance. Addressing research integrity requires tracing its root causes to propose targeted measures. The *Academic Publishing Standards—Definition of Academic Misconduct in Journals* [11] formally defines fabri-

cation and falsification as academic misconduct, which are also important causes of irreproducible research results. According to the *2022 Notification of Investigation Results on Misconduct Cases* released by the National Natural Science Foundation of China [12], a considerable proportion of the 77 scholars penalized for misconduct within six months were found to have fabricated or falsified paper data. Therefore, taking measures to ensure research reproducibility constitutes a crucial step in promoting research integrity construction.

(3) **Necessary means to improve the efficiency of public fund utilization.** In 2018, 31 papers by Professor Piero's team on cardiomyocyte regeneration were found to involve fabricated and falsified experimental data, rendering the results irreproducible. This incident significantly impacted over 50 projects funded by the U.S. National Science Foundation based on this research, causing substantial economic losses and triggering major academic and social controversies. Public skepticism about the reproducibility of many academic findings led to a decline in the credibility of the scientific community. Therefore, ensuring research reproducibility can help prevent or identify problematic papers in advance, avoid waste of research funding, enhance the economic benefits of public funds, and simultaneously maintain academic credibility and improve its social impact.

2 International Mechanisms in the Publishing Process for Ensuring Reproducibility

In the publishing workflow dimension, the TOP Guidelines propose five principles related to research data and processes: (1) Citation Standards: ensuring that data, code, and materials can be properly cited; (2) Data Transparency: encouraging or requiring that data used in papers be properly cited, disclosed, and deposited in designated repositories; (3) Analytic Methods (Code) Transparency: encouraging or requiring that code and analytical methods be properly cited, disclosed, and deposited; (4) Research Materials Transparency: encouraging or requiring that research materials be properly cited, disclosed, and deposited; and (5) Design and Analysis Transparency: reporting standards for study design and analysis should maximize transparency of the research process and minimize ambiguous or incomplete methodological reporting. Academic publishing institutions have adopted relevant measures based on these principles to safeguard research reproducibility.

2.1 Implementing Journal Data Policies to Ensure Research Data Integrity and Reliability

Data constitute the foundation for conducting reproducible research. Publishers such as Springer Nature, Elsevier, Wiley, and Taylor & Francis have all established data policies to support the deposition and storage of various data types, ensure data quality, and enable subsequent sharing and use by researchers.

(1) **Policies to ensure research data integrity.** Data availability statements, as an author declaration mechanism, are increasingly becoming part of the scholarly communication normative system. Code availability statements are also being gradually implemented, effectively improving code-sharing rates for journal articles. For example, the NeurIPS organizing committee launched a reproducibility program in 2019, encouraging (though not mandating) authors to submit code. This initiative has achieved remarkable results: a 2021 report on the reproducibility program indicated that 75% of accepted papers included code [13]. *Biometrical Journal* strongly encourages authors to submit example datasets, source code for data analysis, and other supporting information for online publication [14], with a reproducible research editor reviewing these materials after manuscript acceptance.

In 2020, the American Economic Association (AEA) adopted a Data and Code Availability Policy [15], mandating authors to provide detailed records of data and code and ensuring that other researchers can access the submitted materials, thereby enhancing the reproducibility and transparency of supporting materials in AEA journal articles.

(2) **Policies to ensure research data reliability.** Peer review serves as a crucial method for ensuring data quality. Scientific data peer review, as part of the overall peer review process, requires reviewers to verify the consistency and quality of datasets to ensure their authenticity and reliability. In practice, Springer Nature, Elsevier, and Wiley have all incorporated peer review requirements into their highest-level data policies, stating that authors are obligated to submit all data requested by reviewers. Wiley further proposes that peer review may involve reproducibility verification to ensure that claims in journal articles are valid and reproducible. In 2020, PLOS released a rapid guide for conducting peer review of data, clarifying the questions and evaluation dimensions that reviewers need to address when assessing data.

2.2 Advocating Structured Reporting to Enhance Research Process Transparency

Detailed research processes require authors to clearly describe study conditions, generated data, and experimental procedures. The phenomenon of irreproducible research due to insufficient reporting of methods and results was first identified and examined in the field of neuroscience. Following the identification of this problem, relevant international organizations have advocated for editor-led initiatives to guide authors in report writing. For instance, the International Committee of Medical Journal Editors (ICMJE) requires editors to guide authors in submitting detailed reports of the methods section and specifies detailed reporting requirements for the medical field. The Council of Science Editors (CSE) emphasizes that editors should develop clear guidelines for authors on practices required for reproducible research before and after publication, en-

suring that methods and analyses are sufficiently detailed for readers to evaluate the scientific merit of study designs and replicate the research. These initiatives aim to leverage editors as key reviewing agents to guide, supervise, and examine professional reports that disclose authentic research processes, thereby enabling subsequent researchers to conduct replication experiments smoothly.

In practice, *Nature* first proposed measures in 2013, such as removing length restrictions on the methods section, which further evolved into structured reporting. Currently, major publishing groups have introduced domain-specific structured reports to address two major problems in research process reporting. The first is overly generic descriptions that lack specific structure. Solutions such as *Cell*'s "STAR Methods" and *PNAS*'s "MDAR" (Materials, Design, Analysis, and Reporting) framework require authors to write research procedures in modular formats. The second is insufficient detailed data on parameters and other aspects of the research process. Most publishers now impose strict requirements on the data and methods that must be provided in reports. For example, the NIH requires its medical journals to specify experimental replication numbers, sample sizes, and provide transparent reports to reviewers. Wiley states that its journals across different fields have specialized reporting formats tailored to disciplinary needs and encourages authors to submit strictly according to these formats.

2.3 Promoting Open Peer Review and Innovative Detection Technologies to Verify Research Results

International organizations have proposed supervisory initiatives and measures from two dimensions: peer review models and detection technologies.

(1) **Innovating peer review models** can enhance the transparency of the paper review process, ensure article quality, and improve the reproducibility of scientific research. Open peer review encompasses three levels of openness: reviewer identities, review reports, and the review process itself. Open peer review platforms typically form scholarly communication communities centered on papers, enabling more scholars to participate in paper evaluation and expanding research integrity oversight to the entire research community. These platforms play a significant role in disclosing academic misconduct and enhancing the transparency and reproducibility of scientific research. For example, PubPeer, a third-party open peer review platform developed with NIH support, has exposed multiple image fraud cases involving Japanese cell biologist Haruko Obokata and Nobel laureate Gregg L. Semenza.

(2) **Technologies such as image screening and detection** can identify issues like image manipulation and reuse, thereby verifying the authenticity of research results. Technically identifying artificially modified images or data represents an important method for validating research findings. In 2016, Elsevier established the Humboldt-Elsevier Advanced Data and

Text Center to identify academic misconduct, and in 2018 announced plans to create a "test image database" to improve detection of image manipulation. In 2021, the International Association of Scientific, Technical and Medical Publishers (STM) officially launched the "STM Integrity Hub" service, providing a shared platform to track and examine suspicious document materials, image modifications, and data errors. Dozens of publishers have already joined this initiative.

3 International Mechanisms in Publishing Orientation for Ensuring Reproducibility

In the publishing orientation dimension, the TOP Guidelines propose three principles related to research results and article types: (1) Study Preregistration: requiring authors to preregister their studies before publication, stating research questions and hypotheses to prevent phenomena such as HARKing; (2) Analysis Plan Preregistration: specifying experimental types and methods to prevent irreproducibility caused by research bias; and (3) Replication: requiring journals to encourage replication studies and conduct relevant reviews of their results. These principles provide direction for academic publishing institutions to adjust their orientations and implement measures.

3.1 Establishing Registered Reports to Reduce Bias Against Negative Results

The excessive pursuit of positive results by journals motivates authors to manipulate data to obtain desired outcomes, leading to irreproducible results. The Center for Open Science (COS) initiated and supports a novel submission format called Registered Reports, which represents an ideal workflow for presenting confirmatory, hypothesis-driven research findings. Registered Reports and their unique two-stage peer review model can effectively address the reproducibility crisis caused by research bias and HARKing.

(1) **Registered Reports reduce research bias.** This format allows authors to submit their research questions and methods to journals for peer review before conducting the experiments. Studies that pass this review receive "in-principle acceptance." By making the research question and methodology, rather than the results, the decisive factor for acceptance, this submission format effectively reduces research bias stemming from the academic publishing community's preference for novel, exciting, and positive findings. It alleviates authors' concerns about whether their results will be publishable, thereby weakening the incentive to manipulate data at the source.

(2) **Two-stage peer review prevents HARKing.** The two-stage peer review process for Registered Reports involves an initial peer review after authors have determined their research questions and experimental methods to decide on "in-principle acceptance," followed by a second review

upon study completion to determine final acceptance. This model requires authors to undergo peer review before obtaining results, preventing them from formulating hypotheses after seeing the outcomes and eliminating the possibility of HARKing, thereby ensuring the reliability of research findings.

In 2017, over 40 journals, including the *European Journal of Neuroscience* [16], announced their acceptance of Registered Reports. In February 2023, *Nature* introduced and announced its acceptance of Registered Reports to promote research rigor and reproducibility [17]. According to COS statistics, more than 300 journals now offer Registered Reports as a regular submission option or as part of special issues [18].

3.2 Encouraging Reproducibility Papers to Verify Published Results

Encouraging authors to replicate previously published experiments and conduct replication studies represents another effective measure for ensuring research reproducibility. Replication studies constitute an important component of scientific research, yet publication bias has made them unpopular. To change this situation, the *Journal of Social Psychology*, published by the American Psychological Association (APA), released a special issue inviting researchers to replicate important findings in social psychology. Currently, some publishers have also introduced policies emphasizing the importance of replication studies. For example, Elsevier's *Heliyon* and other journals periodically publish special issues on replication experiments, while *Information Systems* has introduced a dedicated article type for reproducibility papers with designed solutions for reproducibility issues.

Replication studies that independently reproduce previously published results and are written up as separate publications are known as reproducibility papers, which play important roles in safeguarding research reproducibility: (1) Reproducibility papers can verify published research findings, promptly curbing the widespread dissemination of irreproducible papers and reducing economic losses and negative social impacts from their subsequent use. (2) The foundation for developing reproducibility papers lies in the original experiments providing sufficiently detailed data and materials for subsequent replication. Consequently, this article type can also accelerate the deposition process for paper-associated data and promote the adoption of detailed research reporting formats.

3.3 Strengthening Training to Enhance Editors' Capacity to Address Reproducibility Issues

A survey by Malički M et al. [19] indicates that the academic community currently places insufficient emphasis on reproducibility issues, and editors lack support for various aspects of the TOP Guidelines. Therefore, changing the orientation of the academic publishing community requires targeted training for editors, emphasizing the importance of research reproducibility, reversing

editors' preference for positive results, and providing procedural training for reproducibility issues that editors may encounter.

(1) **Strengthening editors' awareness of reproducibility issues and clarifying their responsibilities in reproducibility assurance.** In June 2023, the All European Academies federation (ALLEA) updated the *European Code of Conduct for Research Integrity* [20], emphasizing the responsibilities that research organizations or institutions should shoulder—namely, creating a sound research environment and atmosphere, enhancing researchers' integrity awareness, and ensuring paper reproducibility. The ICMJE considers ensuring paper quality as an important responsibility of journal editors [21], with reproducibility being a key evaluation metric for quality. It is necessary to enhance editors' awareness of paper reproducibility, clarify the responsibilities that editors bear in academic activities, and enable editors to play an effective role in promoting research reproducibility.

(2) **Standardizing editors' operations in handling reproducibility issues.** Journal editors need to adopt standardized procedures for reproducibility issues throughout the academic publishing workflow. The research integrity policy proposed by the U.S. Agency for International Development (USAID) mentions the need to improve oversight processes to prevent bias, fabrication, falsification, plagiarism, external interference, censorship, and inadequate procedural and information security, thereby ensuring scientific transparency and reproducibility. In November 2017, the Committee on Publication Ethics (COPE) introduced new best practices and detailed the contacts and operational procedures editors should follow when discovering irreproducible papers or authors with related research integrity issues. The editorial workflow procedures proposed by COPE have been adopted by publishers such as Elsevier and Wiley, requiring their journal editors to comply.

4 Suggestions for Improving the Reproducibility of China's Scientific Research Outputs

As of June 2023, the Retraction Watch database recorded a total of 19,500 retracted papers with China as the affiliated country, approximately 11,000 of which were retracted due to irreproducible results from various causes. It is urgent to absorb the reproducibility assurance measures from the international academic publishing community and adopt corresponding measures to improve the reproducibility of China's scientific research outputs in light of the current state of our relevant system development.

4.1 Promoting Open Science and Accelerating Deposition of Paper-Associated Data

The core of open science lies in enhancing the transparency and credibility of scientific research through open sharing of research outputs. China's vigorous promotion of research data deposition associated with scientific journal articles in recent years represents an important open science initiative. In terms of infrastructure, Science Data Bank (Science DB), independently developed by the Computer Network Information Center of the Chinese Academy of Sciences in 2015, has become a general-purpose data repository recommended by major international publishers such as Springer Nature, Elsevier, and Taylor & Francis, providing data storage services for tens of thousands of their scientific journals. Regarding deposition policies, the *Measures for the Management of Scientific Data* issued by the General Office of the State Council in April 2018 proposed that "competent authorities and legal entities should actively promote the publication and dissemination of scientific data." Some journals, such as *China Scientific Data* and *Journal of Global Change Data*, have also issued explicit data policies. In terms of practical implementation, the Department of Science and Technology Innovation of the China Association for Science and Technology and the Computer Network Information Center of the Chinese Academy of Sciences jointly organized a specialized training session on research data deposition for scientific journal articles in January 2023, encouraging authors to submit supporting research data during the publication process.

Currently, the number of domestic journals requiring data deposition with explicit guidelines remains limited, and the number of data repositories supporting scientific data deposition and recognized by major international journal publishers is also small. Although China's scientific and journal communities are deepening their understanding of research data deposition for scientific papers, numerous issues still require urgent resolution: scientific datasets are voluminous and structurally complex, while journals lack technical specifications and common practices for data quality control. Additionally, researchers' awareness and motivation for data sharing and citation are insufficient. Accelerated promotion and implementation of data deposition initiatives are still needed.

4.2 Focusing on Cutting-Edge Initiatives and Promoting Innovation in Academic Publishing Models

China's innovation in academic publishing models is currently in the exploratory stage. Regarding peer review models, since 2014, some journals such as *Acta Psychologica Sinica*, *China Scientific Data*, and *Information Science* have pioneered open peer review pilots, implementing features such as public review comments and open public commentary. Additionally, post-publication peer review after paper publication can detect academic misconduct in published papers and serves as an important safeguard for further verifying research reproducibility. Preprint platforms like ChinaXiv, which accept certain postprints and provide open commentary functions, enable open post-publication review

of published papers. In terms of establishing new article types, discussions on preregistration reports in China remain at the conceptual and popularization stage. Wang Yang [22] and colleagues advocate using Registered Reports as a new article type to solve the reproducibility crisis, while Academician Yang Wei [23] proposes using open research infrastructure to guide China's open science governance, pointing out the need to open reproducible research infrastructure and encourage researchers to publish negative results.

It is necessary to intensify efforts in publishing model innovation, encourage publication of new article types, and promote open peer review. Chinese researchers have already shown considerable interest in Registered Reports [24], yet no domestic journals currently accept article types such as Registered Reports or reproducibility papers. Relevant journal policies need to be introduced to advance these formats. Furthermore, academic communities should be accelerated to facilitate scholarly exchange, integrating open peer review into the construction of national high-end platforms for research papers and scientific information, and building in-depth open exchange mechanisms to promote the development of open peer review.

4.3 Improving the Science and Technology Evaluation System to Promote Transformation of Research Concepts

China's traditional scientific evaluation system primarily relies on bibliometrics, emphasizing quantitative indicators such as journal impact factors and paper publication counts, while lacking feedback on the content quality of papers. Improving the scientific evaluation system can assess research output quality more scientifically and accurately, prompting a transformation in researchers' perspectives.

In March 2020, the Ministry of Science and Technology issued the *Several Measures for Breaking the Unhealthy Orientation of "Papers Only" in Science and Technology Evaluation (Trial)* (hereinafter referred to as the *Measures*), highlighting the serious negative impacts of "papers only" and "SCI supremacy" and calling for a series of "combined measures" to break the "four only" orientation (papers only, titles only, education only, awards only) and focus on genuine research outcomes [25]. Following the release of the *Measures*, relevant departments need to formulate specific implementation rules to substantially improve the academic evaluation system. For example, the Xinjiang Science and Technology Department and the Corps Science and Technology Bureau issued the *Implementation Plan for Breaking the Unhealthy Orientation of "Papers Only" in Science and Technology Evaluation (Trial)* in 2022, proposing 32 specific initiatives.

The implementation of the "break four only" policy also requires promoting an evaluation system based on representative works, focusing on the quality, contribution, and impact of landmark achievements to reverse unscientific evaluation orientations [26]. Building on the foundation of big data resources in science

and technology, scholar knowledge bases should be constructed, and text mining technologies should be utilized to conduct correlation analysis of representative works, enhancing the scientific rigor and accuracy of evaluations. Through the improvement of the science and technology evaluation system, researchers' perspectives can be reshaped, research integrity construction can be strengthened, and the reproducibility crisis caused by publishing orientation can be mitigated.

This paper focuses on the academic publishing community using the TOP Guidelines as a framework, systematically analyzing the reproducibility assurance measures and practical progress proposed by international scientific journal publishers, academic associations, and other stakeholders from the two dimensions of publishing workflow and publishing orientation. By comparing these with the domestic situation in China, this study provides directional reference suggestions for domestic academic publishing institutions. Addressing the reproducibility crisis from the perspective of academic publishing also requires exploring specific implementation pathways tailored to the disciplinary fields and publishing practices of China's scientific journals, which represents a direction for future research.

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