

Dynamic evolution and industry trend analysis of China's pharmaceutical industry science and technology innovation network: A bibliometric approach

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Abstract: Background: The pharmaceutical industry is a strategic emerging sector in China, yet its scientific and technological innovation network remains poorly characterized in terms of structural dynamics and evolutionary pathways. **Objectives:** In the field of scientific and technological innovation in China's pharmaceutical industry, this study systematically sorts out the context of research, reveals the structural characteristics and evolutionary laws of the innovation network and provides references for industrial policy formulation and enterprise strategic layout. **Methods:** Based on 602 relevant papers collected from the China National Knowledge Infrastructure (CNKI) from 1996 to 2024, VOSviewer and CiteSpace software were comprehensively used to conduct co-occurrence analysis, cluster analysis and burst term detection, so as to construct a multi-dimensional dynamic network model. **Results:** The number of published papers on scientific and technological innovation in China's pharmaceutical industry increased, with accelerated growth and greater volatility after 2010. A core author group has initially taken shape, but the participation rate of enterprises is only 8.3%, indicating insufficient industry-university-research collaboration. Research hotspots have expanded from traditional biomedicine to emerging technologies such as artificial intelligence-assisted drug design and mRNA vaccines, with industrial clusters and factor collaboration becoming new focuses. **Conclusion:** The innovation of the pharmaceutical industry follows a phased evolutionary path of "technology-driven – cluster development – factor collaboration". At present, it is confronted with structural constraints such as inadequate data sharing, unbalanced resource allocation and a shortage of interdisciplinary talents. It is suggested that enterprises' dominant position in innovation be strengthened, a cross-regional public R and D data platform for the pharmaceutical industry be established, policy incentives shift from project funding to performance-based rewards for innovation alliances and the industry evolve into an adaptive innovation ecosystem.

Keywords: Bibliometrics; Industry report; Knowledge map; Pharmaceutical industry; Scientific and technological innovation network

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INTRODUCTION

The pharmaceutical industry is a strategic emerging industry in China and its capacity for scientific and technological innovation is directly linked to industrial upgrading and the improvement of national health. According to a World Bank report, between 2015 and 2022, China's global competitiveness ranking in the biopharmaceutical industry rose from 12th to 7th, while policy support increased by a factor of 3.1 over the same period (World Bank, 2022). However, pharmaceutical innovation is characterized by the complexity of interdisciplinary integration, multi-agent collaboration and multi-stage interaction (Tierney *et al.*, 2013). This demonstrates the necessity of innovation pattern and evolution studies that detail and provide guidance for appropriate innovation resource allocation and regulation.

The combination of bibliometrics, literature analysis and visualization tools provides a way to analyze the research landscape of innovation in pharmaceuticals. In particular, co-occurrence and network metrics analyses are helpful in

identifying knowledge clusters and research frontiers and in bridging the knowledge gap (van Raan, 2005). Many macro reviews and policy analyses exist; In contrast, very few studies focus specifically on the pharmaceutical industry and analyze the structure, dynamics and evolution of networks of scientific and technological innovations. First, studies tend to concentrate on individual technical domains—for example, biopharmaceutical process optimization (Li *et al.*, 2020)—rather than more comprehensive fields. Second, most research remains static (Tierney *et al.*, 2013) and descriptions of dynamic interaction mechanisms are insufficient. Third, the synergistic effects of policies, technologies, personnel and other factors are severely constrained by limited quantitative methods; Consequently, analyses of the impacts of emerging technologies fail to incorporate dynamic factors. Visualization methods can accurately represent cross-domain knowledge flows in the healthcare industry (Li *et al.*, 2024) and can therefore be applied to analyze knowledge and technological innovation networks in pharmaceuticals.

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This study combines bibliometrics with knowledge mapping techniques to construct a multi-faceted dynamic network model that identifies and conceptualizes the dynamic evolutionary pathways of pharmaceutical science and technology innovation networks. Such knowledge mapping approaches have been widely employed to explore the evolution of innovation networks in the biomedical sector, demonstrating their effectiveness in capturing both network structural characteristics and knowledge diffusion patterns (Liu *et al.*, 2023; Wenya *et al.*, 2024). Furthermore, the model proposes strategies to improve the innovation ecosystem. Grounded in the Triple Helix Model (Etzkowitz and Leydesdorff, 2000) and Competitive Advantage Theory (Porter, 1990), a framework entitled “policy-driven, technology-integrated and subject-coordinated” is established. Using VOSviewer and CiteSpace, network centrality metrics, clustering indicators and other measures are quantified in relation to the networks. Finally, based on the knowledge maps and identified temporal patterns, policymakers can better optimize the distribution and allocation of innovation resources, corporate managers can more effectively evaluate potential collaboration opportunities and researchers can maintain a leading position in cutting-edge science.

MATERIALS AND METHODS

Data sources

The primary data source was the China National Knowledge Infrastructure (CNKI) database. A professional search across three dimensions was conducted with a self-built composite search formula, including industrial subjects (pharmaceutical industry, biopharmaceutical industry, pharmaceutical manufacturing industry), core relationships (innovation network, cooperation network, collaborative innovation) and analytical dimensions (structure, evolution and mechanism). The exact search formula was: SU = ('Pharmaceutical Industry' + 'Biopharmaceutical Industry' + 'Biomedicine' + 'Pharmaceutical Industry' + 'Pharmaceutical Manufacturing Industry' + 'Pharmaceutical Enterprises') AND SU = ('Innovation Network' + 'Cooperation Network' + 'Collaborative Innovation' + 'Innovation Ecosystem' + 'Innovation Capability') AND SU = ('Structure' + 'Evolution' + 'Mechanism' + 'Characteristics' + 'Path' + 'Dynamics'). The search period used was from January 1, 1996 to December 31, 2024 and was conducted on October 31, 2025. Initially, 2,318 relevant literature entries were obtained (Fig. S1).

Literature inclusion and exclusion criteria

Two researchers independently implemented a three-stage process that was well-structured and obvious after following it. After initial deduplication of the literature, non-academic papers and those inconsistent with the research theme were excluded based on titles and

abstracts, leaving 839 articles for full-text careful reading. By performing full-text evaluation, papers with a repetition rate above 15% and non-empirical studies were excluded. Finally, through separate dual assessment (Kappa = 0.82, $p < 0.01$) and additional backward-reference tracing, 602 high-quality papers were ascertained to compose the final analytical dataset, ranging from 1996 to 2024.

Among the 602 papers, those primarily focusing on the pharmaceutical manufacturing industry accounted for 54.3% ($n=327$), the biopharmaceutical industry accounted for 28.6% ($n=172$) and the broader pharmaceutical industry (including pharmaceutical equipment and excipients) accounted for 17.1% ($n=103$). This breakdown reflects the relative research activity intensity across the three dimensions.

Research methods

Node weights were calculated and modular clustering via VOSviewer 1.6.20 was performed (van Eck and Waltman, 2010) to establish the co-occurrence networks. Citation networks were analyzed using CiteSpace 6.3.R1 software, where the Pathfinder algorithm was applied to optimize network structure (Chen, 2016) and research hotspots and their evolutionary trends were identified research hotspots and their evolutionary trends. The reliability of these results was ensured through cross-validation with the two tools ($R^2 = 0.89$), allowing for systematic identification of developmental characteristics within pharmaceutical scientific and technological innovation.

RESULTS

Bibliometric characteristics of research on scientific and technological innovation in China's pharmaceutical industry

Temporal characteristics of publication output

From 1996 to 2024, the total number of publications showed an overall upward trend, but exhibited periodic fluctuations due to policy cycles and technological changes (Fig. 1). During the initial years (1996–2010), research concentrated on conventional biopharmaceuticals, leading to an average annual growth rate of a mere 3.2%. This rate increased to an average of 8.5% during the subsequent period (2011–2024). Research began to include digitalization, smart technologies and advanced biotechnologies. Post-2010, growth rate fluctuations increased significantly, as the standard deviation rose from 1.8 to 4.3. In terms of key node research, policy impacts, technological changes and the urgent need to address public health crises were the main causes of fluctuations in publication counts (Zhang *et al.*, 2021).

Journal distribution

The number of publications in the top ten journals shows a certain degree of specialization (Table 1).

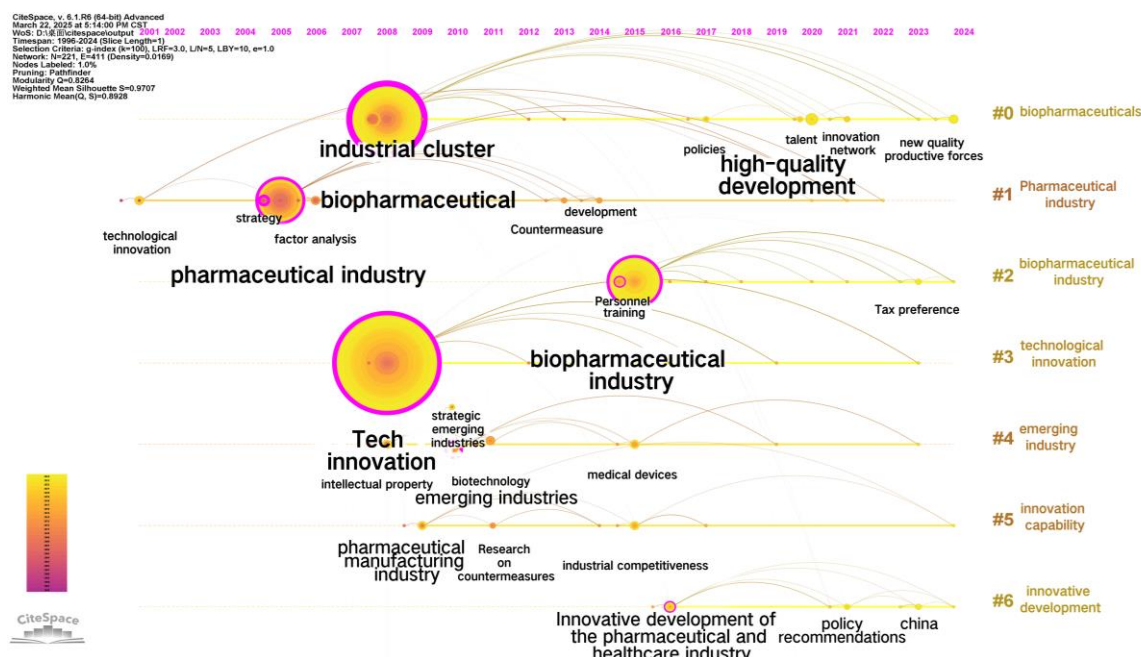


Fig. 1: Temporal analysis of publication output on scientific and technological innovation in the pharmaceutical industry from the CNKI database

Table 1: Distribution of Journal Categories for the Top 10 Journals by Publication Volume on Scientific and Technological Innovation in the Pharmaceutical Industry in CNKI

Distribution of the Top 10 Journals by Publication Volume in Research on Scientific and Technological Innovation in the Pharmaceutical Industry (1996–2024)					
Rank	Journal title	Publication volume	Percentage (%)	2023 Impact factor	Research focus
1	<i>Chinese Journal of New Drugs</i>	18	8.57	2.156	Innovative drug research and development and clinical application
2	<i>Traditional Chinese Drug Research and Clinical Pharmacology</i>	15	7.14	1.874	Modernization of traditional Chinese medicine and pharmacological evaluation
3	<i>Chinese Journal of Pharmaceuticals</i>	12	5.71	1.532	Industrial policy and innovation strategy
4	<i>Science and Technology Management Research</i>	10	4.76	1.289	Scientific and technological innovation management
5	<i>China Pharmacy</i>	8	3.81	1.045	Pharmaceutical economics and market analysis
6	<i>Progress in Pharmaceutical Sciences</i>	7	3.33	0.967	Application of emerging technologies (AIDD)
7	<i>Chinese Journal of Orthopaedics</i>	6	2.86	0.892	Medicine-engineering integration and device innovation
8	<i>Science Research Management</i>	5	2.38	2.41	Innovation networks and competitiveness research
9	<i>Chinese Health Policy Research</i>	5	2.38	1.675	Policy effect evaluation
10	<i>Economic Geography</i>	4	1.9	3.118	Industrial clusters and regional coordination

Data source: CNKI Database; impact factors are quoted from Chinese Academic Journal Impact Factor Annual Report (2023).

Among them, technical RandD journals, such as the *Chinese Journal of New Drugs*, *Traditional Chinese Drug Research* and *Clinical Pharmacology* and *Progress in*

Pharmaceutical Sciences, account for a combined 19.04% of total publications. Meanwhile, policy and management journals, such as *Science and Technology Management*

Research, Science Research Management and *Chinese Health Policy Research*, account for 9.52%, showing that the dominant research direction is technical R and D.

The top five most productive journals have impact factors between 0.967 and 2.156, meaning that practice-oriented journals tend to focus more on this field, as journals with higher impact factors publish less on it.

The research topics of the journals also differ, with *Science Research Management* focusing on the macro level, such as innovation networks and *Progress in Pharmaceutical Sciences* covering emerging technologies and frameworks such as AI-aided drug design. Together, they cover the various dimensions of the field.

Structural characteristics of the scientific and technological innovation network in the pharmaceutical industry

Author collaboration network

There is a noticeable core-periphery system in the author collaboration network (Fig. 2). Hu Haipeng (4 papers, betweenness centrality = 0.42) is a leading first author and his group is significant in biopharmaceutical technology research (total citations = 68, H-index = 3). In accordance with Lotka's law, the top 10% of authors contributed 43.6% of the total publications. The overall density of the collaboration network is very low (0.027) and with only 9.7% of the total being interdisciplinary collaborations, this signals a very limited research scope. Authors such as Hu Haipeng (core author), with a degree centrality of 0.63, act as central nodes for the flow of the entire network. In fact, 72.5% of peripheral authors work in isolation and this large number indicates that the collaborative network system is in urgent need of improvement.

Institutional collaboration network

The structural characteristics of the institutional collaboration network are as follows: (1) The innovation subject structure is unbalanced, with 91.7% of institutions being universities/research institutes and only 8.3% being enterprises (which are at an early stage), demonstrating an extremely low average degree centrality (0.05); (2) The spatial distribution follows a heavy-tailed distribution, where core nodes account for ~72.4% and most geographical representation comes from both the Beijing-Tianjin-Hebei region and the Yangtze River Delta, while the geographic concentration degree in central and western regions falls below ~10%; (3) Regional commercialization is active in Guangdong and Jiangsu, whose collaboration patterns appear constrained (Fig. 3), with cross-regional collaboration limited to just 23.6% and 79.2% of peripheral institutions restricted to regionally defined research (Fig. 3). This pattern of regional concentration and limited inter-regional interaction is consistent with recent findings on the structural characteristics of China's biomedical

collaborative networks. Wenya *et al.*, (2024) similarly observed that collaborative innovation networks between hospitals and biomedical enterprises in China demonstrate high dispersion and poor development levels, with core nodes concentrated in economically developed regions. Although this pattern strengthens first-mover advantages, it can also heighten regional innovation fragmentation and weaken the system's collective resilience.

Research hotspots and evolution paths

Knowledge maps of the research field were constructed from quantitative information using both VOS viewer and Cite Space based on bibliometric principles. Modular clustering of the knowledge network was realized based on the Louvain algorithm. The most important hub node of the network was identified through calculating betweenness centrality.

Keyword co-occurrence and clustering analysis

As a core node, "scientific and technological innovation" forms a strongly correlated triangular structure with "pharmaceutical industry" and "biomedicine", indicating that the interaction between technological innovation and industrial development is the main research line (Fig. 4). The overall network presents a three-dimensional framework of "driven by technological innovation – developed by industrial clusters – supported by factor coordination". The node of "industrial cluster" has high betweenness centrality and acts as an intermediary between topics such as "emerging industries" and "medical devices", marking that the research focus is shifting from single technological breakthroughs to the construction of industrial collaborative ecosystems (Table 2).

The significance of the network structure and the rationality of clustering were verified using the modularity Q value (Modularity Q = 0.8264) and the average silhouette value of clustering (S = 0.9707) (Chen, 2016). The results confirmed a significant clustering structure (Modularity Q = 0.8264, S = 0.9707), with six core clusters formed around "scientific and technological innovation in the pharmaceutical industry" (Fig. 5). Among them, the cluster of biomedical technological innovation focuses on the R and D and industrialization of core technologies such as antibody drugs, CRISPR gene editing and mRNA vaccines (Table 3). Its evolution can be divided into three stages: Policy-driven stage (2000–2010) – antibody drug R and D was funded under the 863 Program (Zhang, 2015); Technology transformation stage (2011–2018) – shared GMP platforms in the Beijing-Tianjin-Hebei biomedical parks reduced R and D costs by 28% (Li *et al.*, 2018); Distributed innovation stage (Post-2019) – for example, the R and D cycle of COVID-19 mRNA vaccines was shortened to 10 months (Zhang *et al.*, 2021).

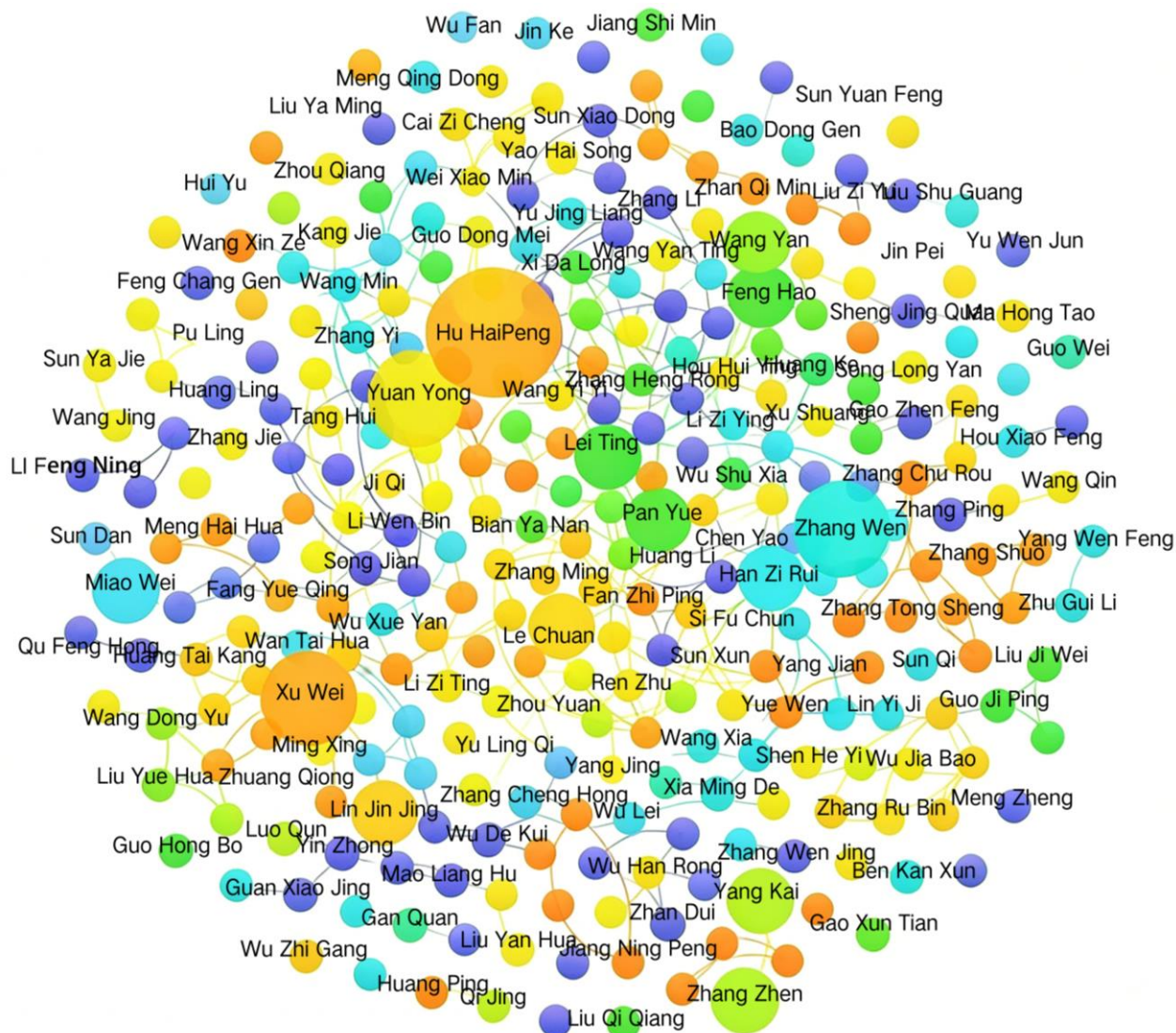


Fig. 2: Analysis of Authors and Collaboration Networks in Publications on Scientific and Technological Innovation in the Pharmaceutical Industry from CNKI

Note: Node size represents the number of publications by an author, line thickness represents collaboration intensity, and core authors are defined as those with betweenness centrality ≥ 0.3 .

The cluster of pharmaceutical industry policy and competitiveness analysis shows that policies such as the Major New Drug Innovation Program and tax incentives have significantly enhanced industrial competitiveness: policy support scores increased 2.1-fold and China's global biomedical competitiveness ranking rose from 12th to 7th (Li *et al.*, 2020); The cluster of collaboration among scientific and technological innovation factors emphasizes the key roles of talent cultivation (Wang *et al.*, 2020), data sharing and industry-university-research collaboration. The cluster of emerging industries and intelligent transformation focuses on emerging fields such as AI-assisted drug discovery (Li *et al.*, 2022) and intelligent medical devices, where the "medicine-engineering integration" model has effectively accelerated innovation (Yang *et al.*, 2022).

Keyword burst detection and stage evolution

From 2005 to 2024, using citation burst detection (Kleinberg algorithm) in CiteSpace, research on scientific and technological innovation in the pharmaceutical industry shows a clear three-stage evolution (Fig. 6).

In the first phase (2005–2008), the focus was on pharmaceutical business and strategy, concentrating on industrial policies and regional-level resource integration. Wu Xiaoming *et al.*, (2007) comprehensively described national industrial policy as the primary driver for building the core foundation. The focus of the second phase (2008–2015) was on the construction of an innovation system, with emphasis on industrial clusters and intellectual property systems. Zhang Jinhua *et al.* (Zhang, 2019)

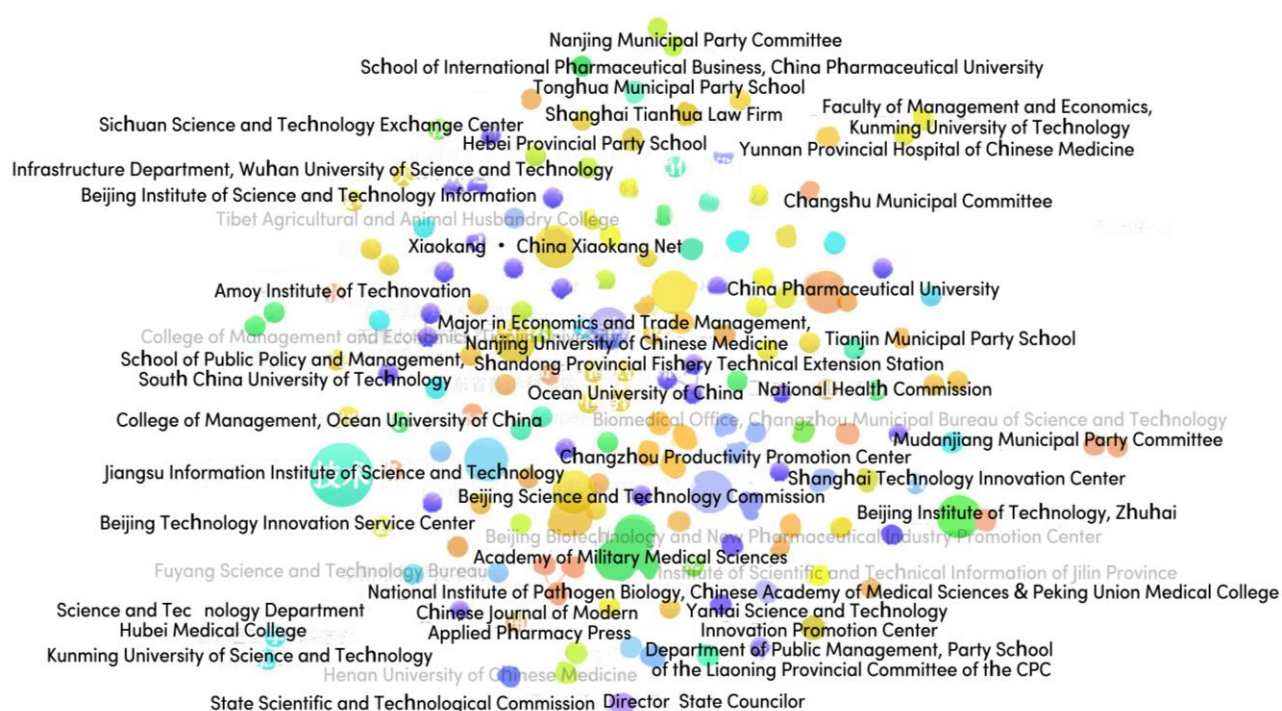


Fig. 3: Mapping of institutional collaboration networks for scientific and technological innovation in the pharmaceutical industry based on CNKI

Table 2: High-frequency keywords in the pharmaceutical industry

No.	Keyword	Frequency	Betweenness centrality
1	Scientific and technological innovation	32	0.63
2	Pharmaceutical industry	22	0.48
3	Biomedicine	14	0.38
4	Industrial cluster	5	0.08
5	Innovation	4	0.02
6	Emerging industries	4	0.03
7	Factor analysis	3	0.04
8	Medical devices	3	0.06
9	Talent cultivation	3	0.03
10	Biotechnology	3	0.01

found a significant positive correlation between the elasticity coefficient of talent mobility and patent output ($\beta=0.83$, $p < 0.01$), highlighting the support of interdisciplinary talent for the closed-loop innovation chain (Zhang, 2019). The third stage (2017–2024) centers on deepened innovation, with achievement transformation and talents becoming research hotspots.

Knowledge map analysis reveals multi-dimensional synergy among “policy–institution–technology” (co-occurrence strength = 1.77). Research themes have shifted from macro strategies to micro technologies and from theoretical exploration to practical application, forming an innovation closed loop of “basic research–technological breakthrough–industrial collaboration”.

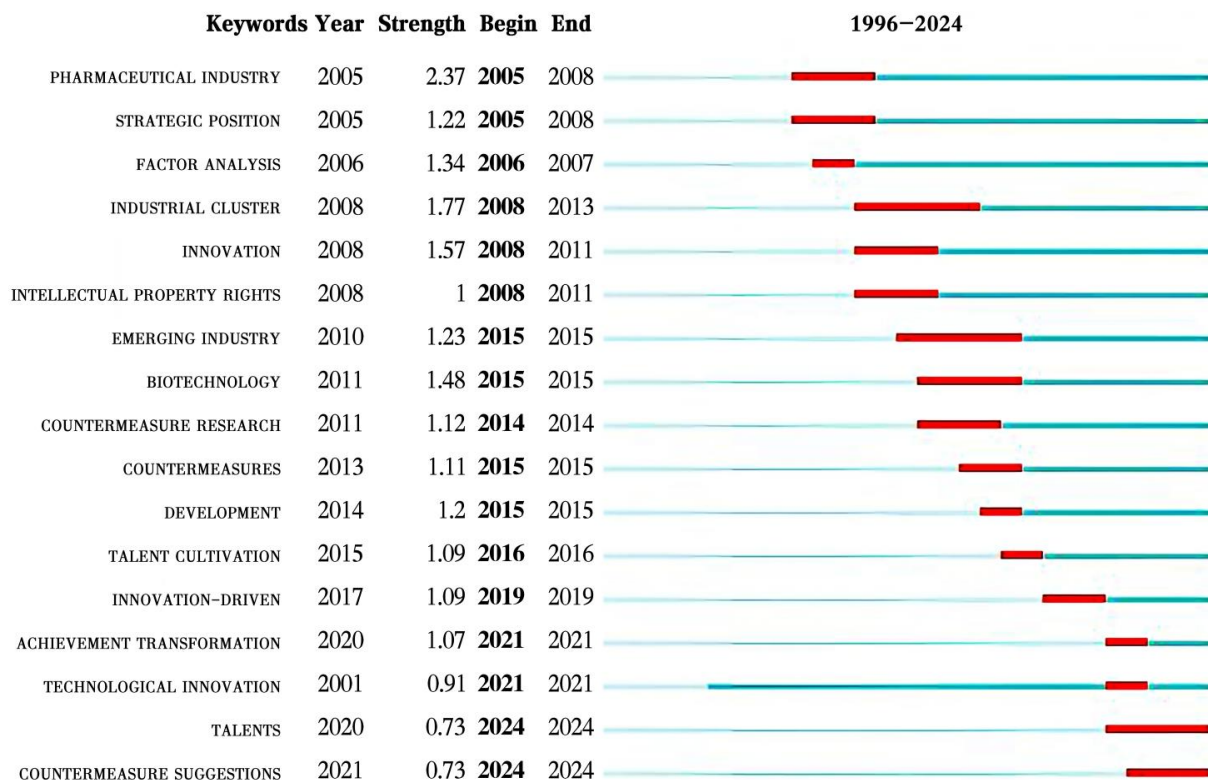
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Table 3: Keyword clustering information of scientific and technological innovation in the pharmaceutical industry from CNKI

Cluster no.	Cluster name	Cluster size	Silhouette value	Cluster content	Representative keywords	Theoretical foundation
#1	Biomedicine	31	0.983	Biomedicine; industrial cluster; electronic information; development trend; Zherong County	Antibody drugs, CRISPR, mRNA vaccines	Triple helix model
#2	Pharmaceutical Industry	29	0.925	Pharmaceutical industry; new drug RandD; system problem archetype; Sichuan Province; framework design	Major new drug innovation, tax incentives	Porter's competitive advantage theory
#3	Biomedical Industry	23	0.924	Biomedical industry; promotion policies; Jiangsu Province; thematic evolution; RandD and innovation	Major new drug innovation, tax incentives	Porter's competitive advantage theory
#4	Scientific and Technological Innovation	20	0.978	Scientific and technological innovation; big health; economic development; characteristics; high-tech industry	Talent cultivation, data sharing	Triple helix model
#5	Emerging Industries	15	0.982	Emerging industries; medical devices; system; spatial layout; guiding principles	AI-assisted drug design, intelligent healthcare	Open innovation theory

Top 17 Keywords With The Strongest Citation Bursts

**Fig. 6:** Keyword burst detection analysis of scientific and technological innovation in the pharmaceutical industry (CNKI)

DICUSSION

Evolutionary laws of the innovation network in the pharmaceutical industry

China's scientific and technological innovation network in the pharmaceutical industry has undergone a three-stage evolution: the policy-driven stage (2005–2008) → the innovation system construction stage (2008–2015) → the deepened innovation stage (2017–2024). Through the closed-loop model of "technological breakthrough – cluster development – factor coordination", this evolutionary path verifies the coupling mechanism of policy, technology and multi-stakeholder collaboration in the Triple Helix Model (Li *et al.*, 2024). At present, the innovation network is evolving from linear technology transformation to a nonlinear ecosystem, with cross-subject collaboration and data-driven innovation emerging as new characteristics.

Current structural constraints

The first part of the bibliometric and knowledge map analyses indicates that the network of scientific and technological innovation in China's pharmaceutical industry presents significant structural imbalance in three dimensions: subject, space and mechanism. As for subject composition, universities and research institutions account for an absolutely dominant proportion (91.7%) of the total records, while enterprise participation accounts for only 8.3%. Furthermore, the high share (81%) of enterprises that rely on technology introduction—compared with only 19% engaged in joint RandD—reflects insufficient motivation at the transformation stage of the innovation chain. In contrast, innovation resources remain concentrated in the Beijing-Tianjin-Hebei region and the Yangtze River Delta (72.4%), whereas the central and western regions contribute less than 10% of China's total innovation resources. Complete Spatial Agglomeration is a potential variant for Earlier Potential First Mover Benefits, Systemic Balance and Resilience and encourages greater re-appraisal of the potential for facilitating Regional Innovation Barriers and the further dismantling value of the system.

With regard to collaborative systems, the total network density is 0.031, which is quite low and inter-regional interaction accounts for only 23.6%. This shows a lack of confidence and trust within organizations, as well as the existence of barriers to sharing. These structural constraints are interrelated and mutually reinforcing and highly restrict collaborative efficiency and the evolution of the pharmaceutical innovation ecosystem.

Limitations

This study only collected literature from the CNKI database, excluding international academic databases. Besides, the analysis of collaboration networks is based on published papers, which cannot fully reflect the actual

cooperation activities among enterprises, universities and research institutions in the pharmaceutical sector.

Implications

The findings clarify the evolutionary characteristics and structural problems of China's pharmaceutical innovation network. The results can assist policymakers in optimizing innovation resource allocation and adjusting incentive policies, and guide relevant institutions to carry out more efficient collaborative innovation.

CONCLUSION

In line with the above findings, the following recommendations are proposed for the innovation ecosystem in the pharmaceutical industry, focusing on a coordinated approach across three dimensions: actors, factors and governance.

First, it is important to further consolidate the leading role of users in innovation. This can be achieved by closely combining the additional RandD deduction policy with the success of industry-university-research alliances, along with the emergence of a pioneering "innovation responsibility community" coordinated by leading industry enterprises. It is suggested to possess higher administrative efficiency, swifter response and stronger internal coordination than regional innovation communities and thus has the greatest potential to substantially address low business involvement and insufficient industry-university-research partnerships. Second, the major focus is on removing barriers to factor mobility on all sides, particularly on the construction of an inter-regional public data platform for pharmaceutical RandD. Initiative, governance and standardized sharing rules are key for the government to transform privately held data into interconnected strategic assets and to eliminate networked data fragmentation, uneven data distribution and poor data utilization.

Third, the incentive model should be shifted toward rewarding "innovation alliances" that continuously produce joint patents and knowledge, rather than providing traditional project subsidies. It is necessary to introduce instruments such as innovation vouchers and matching funds to promote long-term cross-regional cooperation, establishing an adjustable policy framework to support institutional collaboration for innovative and sustainable development.

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Authors' contributions

Li Liqing: Conceptualization, methodology, formal analysis, writing – original draft, writing – review and editing; Liu Jie: Data curation, visualization and validation.

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Data availability statement

All data generated or analysed during this study are included in this published article and its supplementary information files.

Ethical approval

Not applicable. This study is a bibliometric analysis of published literature and does not involve human participants, animals, or personal data.

Conflict of interest

The authors declare no conflict of interest.

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