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Evaluation of the Sustainable Development of Innovation Ecosystem Evolution in High-Tech Enterprises

Abstract. *The sustainable development of the innovation ecosystem of high-tech enterprises is of great significance for integrating innovation resources and shaping the core competitiveness of enterprises. Focusing on the innovation ecosystem of high-tech enterprises in the Beijing–Tianjin–Hebei region, this study constructs an evaluation index system for the sustainable evolutionary development of the innovation ecosystem. Using the entropy weight TOPSIS evaluation model, the evolutionary sustainable development of the innovation ecosystem in the three regions are assessed, and obstacle factors are analysed. The comprehensive evaluation ranking of the sustainable development of the enterprise innovation ecosystem evolution in the three regions can be comprehensively ranked as Beijing, Tianjin, and finally Hebei. Notably, Hebei demonstrates a higher level of symbiotic evolution than Tianjin. From a temporal perspective, Beijing maintains a relatively high level of sustainable development, whereas Tianjin exhibits a decreasing trend, approaching the level of Hebei. In terms of the geographic spatial scope, the sustainable development level of innovation ecosystems in the three regions shows both notable differences and striking similarities, while the obstacle factors in Tianjin and Hebei show similar patterns and trends.*

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1. Introduction

As the key carrier of the national innovation system and the strategic pivot of economic transformation, high-tech enterprises play a key role in reconstructing the landscape of global industrial competition. Through knowledge-intensive technological breakthroughs, they enhance the resilience of national technological

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sovereignty and foster new productive forces in the economy. In April 2023, the first meeting of the 20th Central Committee for Deepening Reform approved the "Opinions on Strengthening the Leading Role of Enterprises in Scientific and Technological Innovation". The meeting pointed out that strengthening the position of enterprises as the main body of scientific and technological innovation is a key measure for deepening the reform of the scientific and technological system and achieving high-level technological self-reliance and self-strengthening. As high-tech industries become increasingly complex, comprehensive, chain-oriented and clustered, improving enterprise competitiveness and innovation efficiency depends on the effective functioning of the innovation ecosystem (Su and Liu, 2018). An innovation ecosystem consists of upstream and downstream enterprises that occupy different ecological niches, yet achieve resource complementarity and mutual influence (Ander and Kapoor, 2010). These enterprises jointly develop new products and services around shared technologies, knowledge, or skills (Moore, 1993; Cao et al., 2023) and promote value creation and innovative development through both competition and cooperation (Khatami et al., 2024). Through multi-dimensional integration, the innovation resources and achievements of the enterprise entities within the ecosystem generate a synergistic effect, enabling shared investment in product research and development, reduced innovation risks, and enhanced core competitiveness of the system. The sustainability of this synergy effect ultimately depends on whether the innovation ecosystem can achieve long-term sustainable development (Ujwary et al., 2025).

In the innovation ecosystem of high-tech enterprises, the allocation of innovation resources and elements, the competitive evolution of innovation populations, and the governance game of innovation subjects are all directed toward achieving a dynamic balance that can adapt to the new environment in a complex and adaptive manner. The ultimate goal is to realise the sustainable development of the innovation ecosystem's evolution. However, this dynamic balance mechanism, akin to that of a natural ecosystem, is easily influenced by factors such as internal and external environmental changes, shifts in competitive relationships among entities driven by innovative interests, and the scarcity of knowledge resources within the system. These factors introduce high uncertainty and complexity, which in turn lead to unsustainable risks, including system collapse and resource waste (Li et al., 2025). Current research primarily focus on the operation mechanism, technical standard pricing, and risk control within the innovation ecosystem of high-tech enterprises, with some attention given to evaluating the evolution and sustainable development of these ecosystems. Nevertheless, there remains a lack of targeted and comprehensive evaluation index systems. To address this gap, this study concentrates on the evaluation of the sustainable development of the innovation ecosystem of high-tech enterprises. It selects indicators from multiple dimensions and constructs an evaluation index system for the sustainable development of ecosystem evolution. By introducing quantitative tools and evaluation methods, and integrating relevant statistical data, this study measures the sustainable development capacity of the innovation ecosystem evolution of high-tech enterprises in the Beijing–Tianjin–Hebei region, aiming to understand their sustainable development levels. Evaluating different

sub-dimensions and identifying obstacles to sustainable development play important guiding roles in proposing targeted measures for the evolution and development of innovation ecosystems among high-tech enterprises.

2. Literature review

2.1 Innovation Ecosystems

The concept of the innovation ecosystem originated from the National Innovation Ecosystem (NIES), a framework proposed by the U.S. Competitiveness Council in 2004, which suggests that improving the level of technological innovation is highly dependent on the innovation ecosystem. Early scholarly attention focused primarily on the conceptualisation and theoretical construction of innovation ecosystems. Drawing on ecological theory and technological innovation theory, Adner (2006) first defined the innovation ecosystem as "a collaborative arrangement in which enterprises combine their respective products into a coherent, customer-oriented solution." Gomes et al. (2018) proposed that an innovation ecosystem is a dynamic network formed through the synergistic effects of multiple subjects, factors, and environments, with its core feature being the enhancement of innovation capabilities and value creation through symbiotic relationships and resource sharing among participants. From a systems perspective, Holgersson et al. (2018) defined the innovation ecosystem as an open system formed by the evolution of various entities through both cooperation and competition. The concept has since been applied in multiple fields, including finance (Palmie et al., 2020) and business (Burstrom et al., 2021). Wang et al. (2023) defined the innovation ecosystem as a complex system composed of entities such as "government, industry, academia, research, finance, and utilisation", arguing that the innovation ecosystem promotes technological innovation output and enhances comprehensive competitive advantages. In terms of theoretical development, scholars have focused mainly on the operation of innovation ecosystems (Wei et al., 2025) and governance (Gu et al., 2025). Teece et al. (2018) suggested that the core of an innovation ecosystem lies in "value proposition, platform architecture, and complementary management," emphasising the central role of technology platforms within the ecosystem. From a co-evolutionary perspective, Wu et al. (2025) pointed out that the emergence of heterogeneous participants at the micro level, co-evolution, and the optimisation of environmental factors collectively promote efficiency improvements in China's open innovation ecosystem.

2.2 Innovation Ecosystem of High-Tech Enterprises

High-tech enterprises rely heavily on innovation ecosystems to address core needs such as technological complexity, resource constraints, and risk diversification. Their market survival mode has shifted from competition between individual enterprises to competition between industrial chains and, ultimately, to competition between innovation ecosystems. The innovation ecosystem of high-

tech enterprises is an innovation system oriented towards customer needs, linked by technical standards and platforms, and formed globally based on supporting technologies that enable coexistence, symbiosis, and co-evolution (Zeng et al., 2013). Previous studies have focused mainly on the operational mechanism of innovation ecosystems in high-tech enterprises, the pricing of technical standards (Zhang et al., 2013), and risk identification and prevention (Zhang and Zheng, 2009). Zhang (2009) noted that the system attracts external innovation through open innovation mechanism, harvests the abundant profits brought by network externalities through promoting technical standards, and achieves complementary advantages through ecological niche decision-making mechanisms. Zhang et al. (2013) identified four pricing strategies for technical standards in the innovation ecosystem of high-tech enterprises: discriminatory pricing, bundled pricing, cross-subsidy pricing, and asymmetric pricing. These strategies provide a reference for technical standard developers to select appropriate pricing models. Only the study by Su and Liu (2018) addressed the sustainable development mechanism of innovation ecosystems in high-tech enterprises. They employed factor analysis and the TOPSIS comprehensive evaluation method to assess the sustainable development of high-tech enterprises across 29 provinces, autonomous regions, and municipalities in China. In related research on innovation ecosystem evaluation, Deng et al. (2025) constructed the CRITIC-TOPSIS model to quantify the competitiveness index of regional green innovation ecosystems (RGIE) and conducted dynamic assessment and configuration path analysis of the RGIE competitiveness index for 30 provinces in China using QCA. Peng et al. (2025) established a health evaluation index system for smart cities and adopted the DEMATEL-TOPSIS method to comprehensively assess the health status of the innovation ecosystem in Wuhan from 2012 to 2020.

In summary, while scholars have extensively investigated the connotation, operation, and governance of innovation ecosystems, research on the innovation ecosystems of high-tech enterprises has focused primarily on operational mechanisms and technical standard pricing, with relatively little exploration of the sustainable development evaluation of the evolution of these ecosystems. Therefore, it is highly important to scientifically and reasonably construct and select an evaluation index system for the sustainable development of ecosystem evolution, and to use the entropy-weight TOPSIS evaluation model to measure the sustainable development capability of innovation ecosystem evolution in high-tech enterprises. Such an approach can help identify obstacles to sustainable development and achieve the innovative development of coexistence, symbiosis, and co-evolution for high-tech enterprises.

3. Design of an Evaluation Index System for Evolutionary Sustainable Development

3.1 Dimensional Analysis

The evolution of the innovation ecosystem of high-tech enterprises constitutes a nonlinear and complex system. Based on previous research (Wang, 2021; Su et al., 2021), this study conducts a comprehensive, multi-level evaluation of the

sustainable development capability of innovation ecosystem evolution from three dimensions: the level of symbiotic evolution, sustainable innovation capability, and the open innovation vitality of the innovation ecosystem of high-tech enterprises.

3.1.1 Level of Symbiotic Evolution

The sustainable development of the innovation ecosystem of high-tech enterprises is characterised primarily by the symbiotic evolutionary relationships among various innovation entities and the symbiotic structural relationships formed through competition, cooperation, and mutual co-evolution of each symbiotic evolutionary unit within the system's innovation environment and resources. Drawing on relevant theories of innovation ecosystems and the composition of innovation elements, this section considers three sub-dimensions, namely, the environment of symbiotic evolution, the structure of symbiotic evolution, and the synergy of symbiotic evolution, to measure the level of symbiotic evolution in the sustainable development of high-tech enterprise innovation ecosystems. Among them, the environment of symbiotic evolution constitutes an important foundational condition for high-tech enterprises to conduct innovation activities. It includes government financial expenditures on regional scientific and technological development, education funding expenditures, per capita GDP, the number of enrolled students and other related policies, as well as basic economic and cultural situations. The collaborative measurement of the symbiotic evolution structure primarily refers to the diversified symbiotic population structure within the system. This includes heterogeneous innovation entities and resources such as the number of high-tech enterprises, R&D institutions, higher education institutions, and social service institutions. The collaborative measurement of symbiotic evolution and the level of collaborative innovation among symbiotic evolution subjects primarily analyses the degree of collaboration and interaction among multiple innovation subjects from the perspective of financial support. This dimension covers four measurement indicators. Among them, the proportion of government funds in R&D funds of high-tech enterprises is government funds/internal expenditures of R&D funds of high-tech enterprises, as reported in the China High-Tech Industry Statistical Yearbook. The proportion of local fiscal technology expenditures to fiscal expenditures is the science and technology budget expenditures/general public budget expenditures, as reported in local statistical yearbooks. The proportion of enterprise funds in university science and technology activity funds is the internal expenditure of enterprise funds/university R&D funds, as reported in the China Science and Technology Statistical Yearbook. The proportion of enterprise funds in the scientific and technological activity funds of research institutes is the ratio of enterprise funds in local statistical yearbooks to the internal R&D expenses of research institutes.

3.1.2. Continuous Innovation Capability

To characterise the sustainable development potential of the innovation ecosystem, the sustainable innovation capability of the high-tech enterprise innovation ecosystem is measured primarily from the dimensions of innovation

resource input and performance output. Under a favourable level of symbiotic evolution among various innovative entities within the system, the stable investment of innovation resources and the virtuous-cycle transfer and transformation of achievements serve as the driving forces for the operation and upgrading development of the innovation system. The dimension of innovation resource input includes three main measurement indicators, while the dimension of innovation performance output includes four main measurement indicators. The proportion of product exports to commodity exports is defined as the ratio of high-tech product exports to major commodity exports, as reported in various statistical yearbooks (e.g., the Hebei Statistical Yearbook). The indicator of patent ownership transfer and licence income has been omitted due to the unavailability of public data for certain years.

3.1.3 Vitality of Open Innovation

The open innovation vitality of the innovation ecosystem of high-tech enterprises is an important dimension for measuring its sustainable development and is reflected in two ways: the openness of the system and the circulation of achievements. Internal entities within the ecosystem continuously engage in multi-level exchanges and cooperation with the external environment in terms of knowledge, information, funding, and technology. Higher levels of engagement are associated with greater potential for system development. Drawing on the relevant literature (Wang, 2021; Qi et al., 2016) and incorporating the characteristics of high-tech enterprises and the available data in statistical yearbooks, the expenditure on technology digestion and absorption funds has been excluded due to the unavailability data for certain years. Accordingly, the levels of system openness and achievement circulation are measured primarily from two dimensions.

3.2 The Index System for Sustainable Development Evaluation

Based on the above analysis, this study constructs an evaluation system for the sustainable development of innovation systems in high-tech enterprises. It measures three target layers (level of symbiotic evolution, sustainable innovation capability, and open innovation vitality), seven secondary indicators, and twenty-four tertiary indicators. The definitions of each indicator are presented in Table 1.

Table 1. Evaluation Index System for the Sustainable Development of Innovation Ecosystem

Measurement target	Leading factor	Measurement index
Symbiotic evolution level	Environment of symbiotic evolution	Government expenditure on science and technology (unit: CNY one billion) x_1
		GDP per capita (unit: CNY) x_2
		Number of enrolled students per 10,000 population (unit: persons) x_3
		Education expenditure (unit: CNY one billion) x_4
	Structure of symbiotic evolution	High-tech enterprises (unit: number) x_5
		Higher education institutions (unit: number) x_6
		Social service institutions (unit: number) x_7
		R&D institutions (unit: number) x_8

Measurement target	Leading factor	Measurement index
	Symbiotic evolution and synergy	Proportion of government funding in high-tech enterprises' R&D expenditure (%) x_9
		Proportion of local government science and technology expenditure in total fiscal expenditure (%) x_{10}
		Proportion of enterprise funding in higher education institutions' science and technology activity funding (%) x_{11}
		Proportion of enterprise funding in scientific R&D institutions' science and technology activity funding (%) x_{12}
Sustainable innovation capability	Innovative resource investment	Intramural R&D expenditure (unit: CNY 10,000) x_{13}
		Full-time equivalents (FTEs) of R&D personnel (person-years) x_{14}
		New product development expenditure (unit: CNY 10,000) x_{15}
	Innovation performance output	Number of patent applications (unit: number) x_{16}
		Number of valid invention patents (unit: number) x_{17}
		Proportion of product exports in total commodity exports (%) x_{18}
		Sales revenue of new products (unit: CNY 10,000) x_{19}
Open innovation vitality	System openness	Expenditure on technology acquisition (unit: CNY 10,000) x_{20}
		Expenditure on technical renovation (unit: CNY 10,000) x_{21}
	Achievement liquidity	Import and export trade in high-tech products (unit: million USD) x_{22}
		Expenditure on domestic technology acquisition (unit: CNY 10,000) x_{23}
		Transaction value of technology exports in the technology market (unit: CNY 10,000) x_{24}

Source: Authors' processing.

4. System Evolution Sustainable Development Evaluation based on the Entropy Weight TOPSIS Model

4.1 Entropy Weight Method

The entropy weight method is a widely used approach for eliminating subjectivity in the determination of indicator weights. According to the principle of information entropy, the smaller the entropy value of a given indicator, the more stable it is, and the greater its impact on the comprehensive evaluation. In this study, data on 24 indicators were collected from three provinces and municipalities from 2015 to 2022, forming the basis of an indicator system data matrix $X = (x_{ij})$, $i = 1, 2, 3$, $j = 1, 2, \dots, n$. For each year t , the decision matrix is defined as $x_{ij}(t_k)$, where x_{ij} represents the data of the i -th region and the j -th indicator, $k = 1, 2, \dots, 10$. The matrix constructed from the original evaluation data is X as follows:

$$X_{ij} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}_{mn}$$

Therefore, the steps to improve the entropy weight are as follows:

(1) Non-dimensional processing of data

Most of the indicators have different types and inconsistent data units, and data preprocessing is needed to eliminate the impact of dimensional inconsistency. The extreme value method is used to process the data and make them dimensionless, as shown in formulas (1) and (2):

Positive indicators X_j :

$$X'_{ij} = (X_{ij} - \min\{X_j\}) / (\max\{X_j\} - \min\{X_j\}) \quad (1)$$

Negative indicators X_j :

$$X'_{ij} = (\max\{X_j\} - X_{ij}) / (\max\{X_j\} - \min\{X_j\}) \quad (2)$$

Where $\max\{X_j\}$, $\min\{X_j\}$ represents the data of the i -th region and j -th indicator after dimensional processing the maximum and minimum values of the j -th indicator, respectively.

(2) Feature weight

The proportions of the i -th and j -th indicators in the i -th region are calculated as shown in equation (3):

$$e_{ij} = X'_{ij} / \sum_{i=1}^n X'_{ij} \quad (3)$$

In the formula, e_{ij} represents the proportion of the j -th indicator in the i -th region.

(3) Entropy value

The entropy value of the j -th indicator is shown in equation (4)

$$e_j = -k \sum_{i=1}^n e_{ij} \ln e_{ij} \quad (4)$$

In the formula, $k = 1/\ln n$, where n is the number of evaluation indicators, e_j denotes the entropy, and the information deviation coefficient is given by $g_j = 1 - e_j$.

(4) Entropy weight

The weight of the evaluation indicators is $\omega = \omega_1, \omega_2, \dots, \omega_n$, where ω_j is the entropy weight to which the j th indicator belongs, as shown in equation (5).

$$\omega_j = \frac{1 - e_j}{n - \sum_{j=1}^n e_j} \quad (5)$$

4.2 TOPSIS-based sorting method

TOPSIS is based on the degree of proximity between the evaluation object and the ideal solution target to sort. This method was proposed in 1981 and is commonly used for multi-objective and multi-index decision evaluation problems.

The operation process is simple, and the evaluation results are objective (Qi et al., 2016; Deng et al., 2025). The steps are as follows:

(1) Construct a normalised decision matrix X and process the matrix constructed by the indicator values, as shown in equation (6).

$$x''_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \tag{6}$$

(2) Based on the improved entropy weight, construct a weighted decision matrix, as shown in equation (7):

$$D = X''_{ij} \cdot W_j = \begin{bmatrix} d_{11} & \cdots & d_{1j} \\ \vdots & & \vdots \\ d_{i1} & \cdots & d_{ij} \end{bmatrix} \tag{7}$$

(3) Determine the ideal and negative ideal solutions for each indicator, as shown in equations (8) and (9), respectively.

$$x_j^+ = \max\{x_{ij} | 1 \leq i \leq 10\}; x^+ = (x_1^+, x_2^+, \dots, x_m^+) \tag{8}$$

$$x_j^- = \min\{x_{ij} | 1 \leq i \leq 10\}; x^- = (x_1^-, x_2^-, \dots, x_m^-) \tag{9}$$

(4) Determine the distances between each region and the positive and negative ideal solutions, namely, the optimal distance d_i^+ and the worst distance d_i^- , as shown in equations (10) and (11), respectively.

$$d_i^+ = \sqrt{\sum_{j=1}^n (d_{ij} - x_j^+)^2} \tag{10}$$

$$d_i^- = \sqrt{\sum_{j=1}^n (d_{ij} - x_j^-)^2} \tag{11}$$

(5) Determine the degree of closeness T_i for each region, which measures the evolutionary sustainability of regional enterprise innovation ecosystems by their distance to the positive and negative ideal solutions. Rank the regions in descending order of T_i , where a higher value indicates closer alignment with the optimal solution. The selection criteria for the optimal solution are given by Eqs. (12) and (13).

$$T_i = d_i^- / (d_i^+ + d_i^-) \tag{12}$$

$$T_i^* = \max\{T_i | i = 1, 2, \dots, n\} \tag{13}$$

5. Evaluation of Sustainable Development of Enterprise Innovation Ecosystem Evolution: A Case Study of the Beijing–Tianjin–Hebei Region

5.1 Data Sources and Handling of Missing Values

The innovation ecosystem of high-tech enterprises in Beijing, Tianjin, and Hebei were selected as the evaluation objects. Data were collected from a wide range of sources, including the China Statistical Yearbook on High-Tech Industries, the China Statistical Yearbook on Fixed Asset Investment, the China Statistical Yearbook on Science and Technology, the provincial and municipal statistical yearbooks of Beijing, Tianjin, and Hebei, the regional science and technology statistical yearbooks, the statistical bulletin on science and technology investment, as well as supplementary data from the Report on Regional Innovation Capability Evaluation and the bulletins on national economic and social development of Beijing, Tianjin, and Hebei. Given that most indicator data for 2024 have not yet been released, the study period was primarily based on raw data from 2015 to 2023. Furthermore, due to the non-disclosure of data for several years for indicators such as technology digestion and absorption expenses, patent ownership transfer, and licence revenue, these indicators were excluded. The final dataset thus consists of the 24 tertiary indicators. To address missing raw data for certain indicators in a specific year, linear interpolation was used to fill the gaps. Taking Hebei Province as an example, the evaluation indicators for the sustainable development of the innovation ecosystem evolution of high-tech enterprises within the province are presented in Table 2.

Table 2. Evaluation Index Values for the Sustainable Development of Innovation Ecosystem Evolution of High-Tech Enterprises in Hebei Province

Measurement index	2015	2016	2017	2018	2019	2020	2021	2022	2023
x_1	45.50	73.18	69.08	77.04	90.70	101.76	112.64	118.13	131.04
x_2	35994	38688	41451	43808	47036	48302	54181	56995	59332
x_3	1910	1964	2032	2106	2173	2234	2274	2250	2243
x_4	1286.16	1420.38	1593.85	1738.96	1992.12	2128.28	2192.78	2439.58	2192.78
x_5	633	633	641	650	670	745	840	939	953
x_6	118	120	121	122	122	125	123	124	128
x_7	9521	9775	9924	13593	13573	8705	8415	8946	9481
x_8	167	182	170	159	293	321	382	567	596
x_9	8.01	7.05	5.44	3.82	11.84	2.33	3.16	2.87	2.03
x_{10}	0.81	1.21	1.04	1.00	1.09	1.13	1.27	1.27	1.36
x_{11}	27.03	24.02	23.87	24.50	24.20	40.17	37.01	40.77	41.02
x_{12}	0.14	0.17	0.40	0.02	2.38	0.08	0.02	0.12	0.02
x_{13}	387330	409416	422877	436338	340203	585337	473430	721132	783479
x_{14}	13694	14151	12064	9977	10482	10919	10295	14015	16868
x_{15}	343124	390058	446775	503492	497992	674165	675328	787771	903120
x_{16}	1172	1553	1593	1633	4111	3059	3462	3898	4117
x_{17}	1899	2603	2988	3373	3716	4464	5528	6578	7869
x_{18}	7.16	6.21	6.94	8.44	8.86	8.42	7.65	7.67	7.09
x_{19}	3410594	3889455	4575594	5261734	6230760	7158532	8823196	7859602	8421008
x_{20}	4202	3729	4009	4289	1291	514	358	202	46
x_{21}	48183	32259	37455	42652	25268	21852	29701	53575	19917

Measurement index	2015	2016	2017	2018	2019	2020	2021	2022	2023
x_{22}	328261	296992	318813	536376	439005	415487	467566	467926	435385
x_{23}	9468	7556	8504	9452	37343	46324	105015	101087	57905
x_{24}	395438	589959	889245	2759840	3811904	5549646	7473182	10038253	17830882

Source: Authors' processing.

5.2 Comprehensive Evaluation of Sustainable Development

5.2.1 Dynamic Entropy Weight Calculation

Based on the evaluation model and entropy weight method constructed in the previous section, the collected data were first standardised. Subsequently, the weights of each indicator for different years were calculated. The resulting dynamic entropy weights are shown in Table 3.

Table 3. Entropy weight of each indicator

Indicator weight (%)	2015	2016	2017	2018	2019	2020	2021	2022	2023
x_1	4.36%	4.88%	5.18%	5.94%	6.01%	5.77%	6.60%	4.97%	4.37%
x_2	3.63%	3.77%	3.48%	3.34%	3.20%	3.03%	3.29%	3.18%	2.78%
x_3	3.31%	3.43%	3.16%	3.00%	2.92%	2.86%	2.89%	2.99%	2.63%
x_4	3.80%	3.95%	3.53%	3.42%	3.30%	6.14%	3.46%	3.52%	2.82%
x_5	5.16%	4.10%	3.46%	3.17%	3.18%	2.81%	2.89%	2.78%	2.41%
x_6	3.55%	3.61%	3.33%	3.20%	3.05%	2.91%	3.10%	3.05%	2.68%
x_7	3.29%	3.36%	3.08%	2.94%	2.82%	3.22%	3.24%	3.00%	3.06%
x_8	5.51%	4.43%	3.83%	3.42%	3.02%	2.81%	3.46%	4.14%	4.14%
x_9	3.46%	4.55%	5.18%	2.95%	3.72%	3.93%	4.16%	4.69%	6.12%
x_{10}	3.35%	3.43%	3.28%	3.26%	3.36%	2.85%	3.40%	4.42%	4.00%
x_{11}	6.83%	3.42%	3.05%	3.10%	3.68%	2.95%	2.82%	2.77%	2.53%
x_{12}	3.79%	3.72%	3.10%	2.93%	3.30%	2.93%	2.89%	2.78%	2.43%
x_{13}	3.58%	4.33%	4.15%	4.14%	4.77%	5.32%	4.37%	4.95%	5.24%
x_{14}	3.29%	4.10%	4.51%	5.29%	4.77%	4.94%	3.40%	5.24%	5.07%
x_{15}	4.41%	5.96%	5.39%	5.07%	5.70%	5.61%	6.20%	5.76%	5.96%
x_{16}	4.46%	4.67%	4.81%	5.29%	4.77%	4.36%	5.32%	5.90%	5.93%
x_{17}	4.54%	4.74%	4.90%	5.07%	5.70%	5.32%	6.20%	6.23%	5.70%
x_{18}	3.30%	3.30%	3.05%	2.93%	2.81%	2.79%	3.65%	3.32%	2.42%
x_{19}	3.26%	3.31%	3.24%	3.67%	5.07%	4.73%	5.57%	4.11%	4.42%
x_{20}	3.25%	3.40%	3.25%	3.26%	6.37%	6.58%	4.37%	3.18%	6.20%
x_{21}	3.71%	3.39%	3.43%	5.29%	3.86%	2.68%	2.82%	4.17%	3.37%
x_{22}	6.68%	6.70%	7.67%	7.10%	6.80%	6.35%	6.83%	6.65%	5.73%
x_{23}	3.67%	3.48%	6.19%	6.45%	3.36%	3.93%	3.34%	2.79%	4.27%
x_{24}	5.80%	5.96%	5.76%	5.79%	5.42%	5.18%	5.72%	5.42%	5.73%

Source: Authors' processing.

According to Table 3, the weights of each indicator dynamically change from 2015 to 2023. Within the dimension of symbiotic evolution level, indicators x_1 to x_4 represent the environment of symbiotic evolution. The weight of fiscal technology expenditure (x_1) remains consistently high each year, indicating its strong influence. In contrast, the weight of students per 10,000 population (x_3) is relatively low, suggesting that this indicator has a limited impact on the environment of

symbiotic evolution. Indicators x_5 to x_8 represent the structure of symbiotic evolution. The weights of high-tech enterprises (x_5) and R&D institutions (x_8) are relatively close and, in most years, higher than those of higher education institutions and social service institutions. This finding indicates that, within the structure of symbiotic evolution, the number of high-tech enterprises and R&D institutions plays a more important structural role. The indicators x_9 to x_{12} represent symbiotic evolution and synergy. In recent years, the weight of government funds (x_9) in the R&D budget of high-tech enterprises has been increasing, while the weight of enterprise funds (x_{12}) in the activity budgets of scientific R&D institutions has remained relatively low. This indicates that the synergistic effect of government funds on the R&D budget of high-tech enterprises is prominent, whereas the synergistic effect of enterprise funds on scientific R&D institution is comparatively limited. Overall, the dimension of symbiotic evolution exerts a significant effect on the sustainable development of the innovation ecosystem of high-tech enterprises, with a total weight approaching 50%.

In the dimension of sustained innovation capability, indicators x_{13} to x_{15} represent the investment of innovation resources. The weight of new product development expenditure (x_{15}) has consistently been relatively high, indicating that high-tech enterprises place greater emphasis on expenditure for new product development. Indicators x_{16} to x_{19} represent innovation performance output. The weights of patent applications (x_{16}) and effective invention patents (x_{17}) are generally greater than those of the proportion of product exports to commodity exports (x_{18}) and new product sales revenue (x_{19}). This finding suggests that the performance output of high-tech enterprises is primarily reflected in the R&D output of patent technology and the accumulation of technology, while the weights of product exports and new product sales are relatively low. The values of these latter two indicators require a longer period to be fully realised. In the dimension of open innovation vitality, indicators x_{20} and x_{21} represent the openness of the system, with the weights of these two indicators alternating between increases and decreases. The indicators x_{22} to x_{24} represent the circulation of achievements. The import and export trade in high-tech products (x_{22}) and the output of technology in the technology market (x_{24}) are clearly more important than expenditure on domestic technology (x_{23}). Thus, the circulation of the innovative achievements of high-tech enterprises is reflected mainly in the import and export trade in high-tech products and the output of technology in the technology market, while the role of domestic technology expenditure remains limited.

5.2.2 Entropy Weight TOPSIS Posting Progress and Sorting

Following the entropy-weight TOPSIS ranking method constructed earlier, a weighted decision matrix was first built by incorporating the entropy weights to determine the ideal and negative ideal solutions of each indicator. Subsequently, the relative proximity of each indicator to the ideal solution was calculated for each region, and the ranking was determined accordingly. The relative proximity and ranking results for the sustainable development level of the innovation ecosystem

evolution of high-tech enterprises in the Beijing–Tianjin–Hebei region are shown in Table 4.

Table 4. Progress and ranking of similar indicators in the Beijing–Tianjin–Hebei region

Area	2015	2016	2017	2018	2019	2020	2021	2022	2023	Average progress of posting	ranking
Beijing	0.628	0.713	0.695	0.671	0.663	0.650	0.675	0.652	0.667	0.668	1
Tianjin	0.470	0.390	0.385	0.360	0.367	0.322	0.347	0.334	0.276	0.372	2
Hebei	0.317	0.319	0.281	0.309	0.299	0.310	0.294	0.323	0.310	0.306	3

Source: Authors’ processing.

According to Table 4, Beijing exhibits the highest degree of proximity at 0.668, followed by Tianjin, while Hebei ranks third in terms of the sustainable development level of the innovation ecosystem evolution of high-tech enterprises. From a temporal perspective, Beijing remained relatively stable between 0.6 and 0.7 throughout the 2015-2022 period, consistently maintaining a high level of sustainable development. In contrast, Tianjin has shown a gradual downward trend, declining from an early level of 0.470 to 0.334 in 2022. This decline aligns with the region's overall pattern of weak GDP growth and insufficient economic development vitality over the past decade. Hebei has remained at a stable level and is progressively approaching Tianjin, although a considerable gap remains compared with Beijing. The temporal dynamics of the Beijing–Tianjin–Hebei region are illustrated in Figure 1.

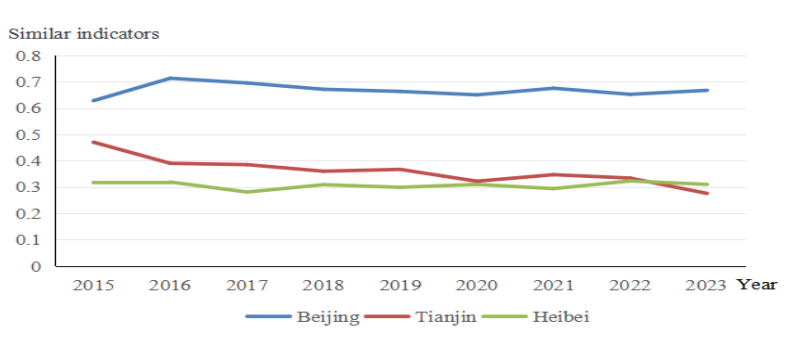


Figure 1. Time series changes in the progress of similar indicators in the Beijing–Tianjin–Hebei region

Source: Authors’ own creation.

The evaluation system for the sustainable development of the innovation ecosystem of high-tech enterprises comprises three dimensions: the level of symbiotic evolution, sustainable innovation capability, and open innovation vitality. The similarity and closeness of the evolution and sustainable development of enterprise innovation ecosystems in the Beijing–Tianjin–Hebei region are examined from three dimensions, and their dynamic trends are shown in Figure 2. As shown in Figure 2, in terms of open innovation vitality, the development levels of the Beijing–Tianjin–Hebei region are relatively close; compared with Tianjin

and Hebei, Beijing has a relatively high level of closeness in terms of its level of symbiotic evolution and sustainable innovation capability, and it has significant advantages compared to Tianjin and Hebei. Tianjin's overall level of sustainable development in the enterprise innovation ecosystem is ahead of that of Hebei, but in terms of symbiotic evolution, the development level of Tianjin is not weaker than that of Tianjin and is even stronger. In terms of sustained innovation capability, Tianjin has a significant advantage over Hebei. In terms of open innovation vitality, Tianjin and Hebei are at the same level. Overall, the sustainable development level in Hebei is lower than that of Beijing and Tianjin, but after years of development, the gap with Tianjin has become smaller and smaller.

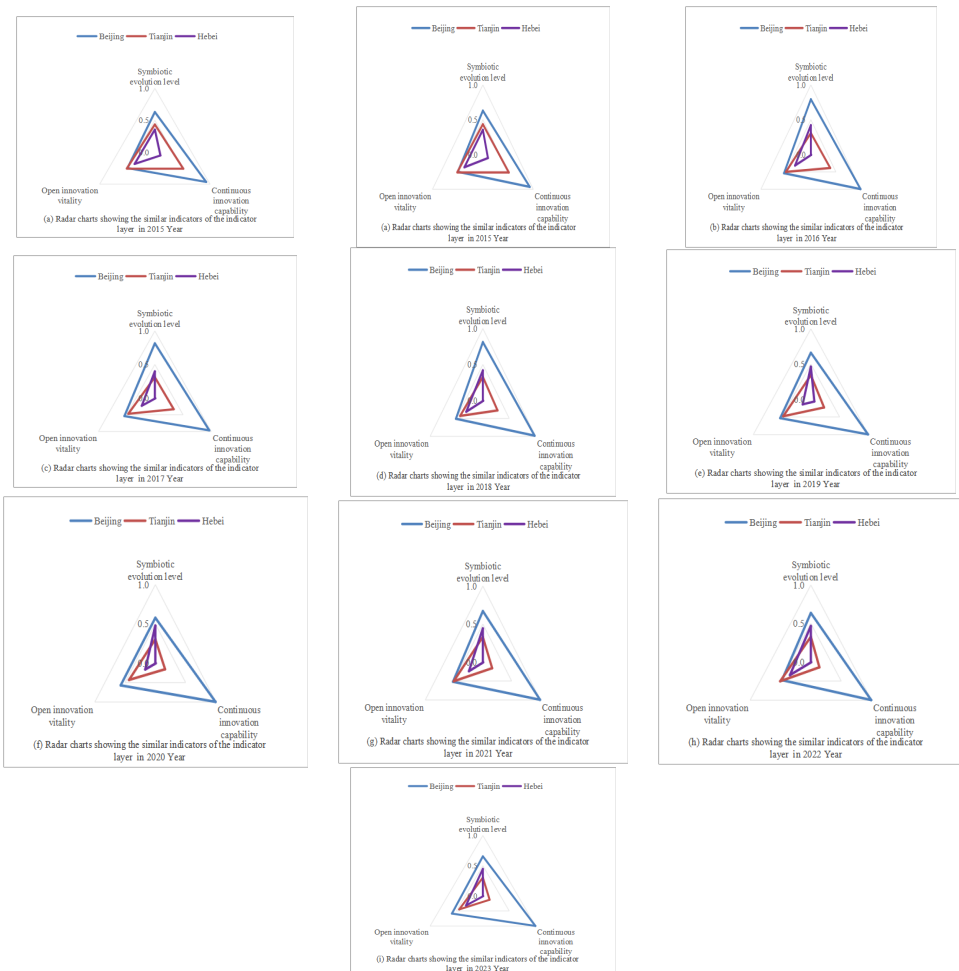


Figure 2. Radar charts showing the similar indicators of the indicator layer from 2015-2023 year

Source: Authors' own creation.

Taking the dimension of symbiotic evolution level as an example, the progress results for the Beijing–Tianjin–Hebei region are shown in Figure 3. Based on the average proximity scores from 2015 to 2022, the average values for Beijing, Tianjin, and Hebei are 0.670, 0.335, and 0.430, respectively. Thus, Beijing ranks first in development level, Hebei ranks second, and Tianjin ranks third. When the proximity scores for the dimensions of sustainable innovation capability and open innovation vitality are calculated similarly, Beijing again ranks first, followed by Tianjin in second place, and Hebei in third.

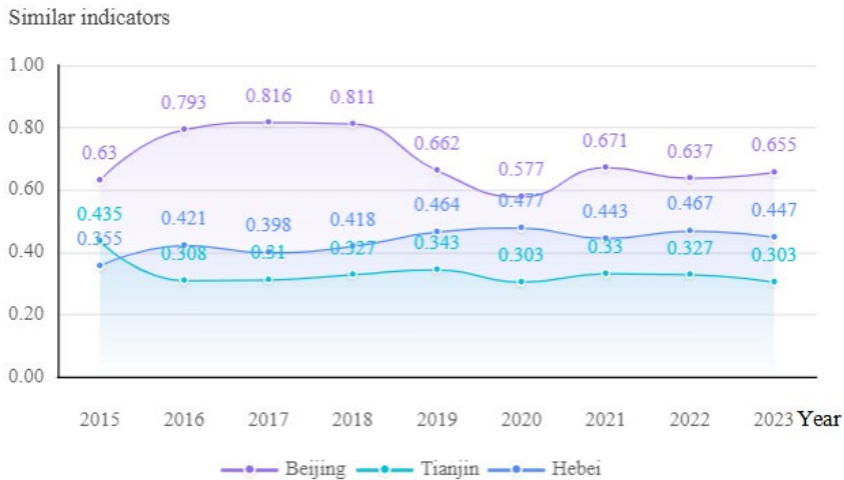


Figure 3. Similar indicators of Levels of Symbiotic Evolution

Source: Authors' own creation.

5.3 Obstacles to Sustainable Development

5.3.1 Obstacle Degree Model

As a mathematical statistical method, the obstacle degree model measures the contribution and obstacle degree of influencing factors based on three levels: the factor contribution degree, deviation degree, and obstacle degree. In the previous section, an evaluation index for the sustainable development of the innovation ecosystem of high-tech enterprises was constructed, with secondary indicators including the three dimensions of the level of symbiotic evolution, sustained innovation capability, and open innovation vitality, as well as multiple tertiary indicators. The specific analysis steps of the obstacle degree model are as follows:

(1) Calculate the contribution of factors to the evolution and sustainable development of each innovation ecosystem W_j , represented by the weight of the j -th indicator.

(2) Calculate the deviation degree of indicators for the evolutionary sustainability of the innovation ecosystem as $M_{ij} = 1 - X_{ij}$, where X_{ij} represents the dimensionless value of the j th indicator in the i -th year.

(3) Calculate the obstacle degree of a single indicator to the sustainable development of the innovation ecosystem evolution, as shown in equation (14):

$$O_{ij} = M_{ij} \cdot W_j / \sum_{j=1}^n M_{ij} \cdot W_j \times 100\% \tag{14}$$

where O_{ij} represents the obstacle degree of the j -th indicator in the i -th year to the sustainable development of the innovation ecosystem evolution and n is the number of evaluation indicators.

5.3.2 Analysis of Obstacle Degree Factors

(1) Analysis of Obstacle Factors in the Level of Symbiotic Evolution

Regarding the level of symbiotic evolution, the main obstacles to the sustainable development of the innovation ecosystem of high-tech enterprises in Beijing, Tianjin, and Hebei vary across regions and years, as shown in Table 5. From a spatial distribution perspective, the main obstacles in Beijing are education expenditure, the number of R&D institutions, and occasionally the proportion of government funds in high-tech enterprise R&D funds and enterprise funds in university science and technology activity funds. In Tianjin, the main obstacle factors are the number of R&D institutions and the proportion of government funds in high-tech enterprise R&D funds before 2018, and the shift to fiscal technology expenditure and education expenditure after 2019. In Hebei, the primary obstacle is fiscal technology expenditure. Notably, fiscal technology expenditure is a major obstacle to the development of the level of symbiotic evolution in both Tianjin and Hebei, whereas Beijing focuses mainly on education expenditure and the number of R&D institutions, reflecting distinct regional differences.

Table 5. Main Obstacles to the Level of Symbiotic Evolution

Area	factor	2015	2016	2017	2018	2019	2020	2021	2022	2023
Beijing	Obstacle factor	x_{11}	x_4	x_4	x_4	x_{11}	x_4	x_{11}	x_8	x_8
	Obstacle level (%)	26.87	16.23	13.49	10.96	10.50	25.61	12.91	13.30	15.20
Tianjin	Obstacle factor	x_8	x_9	x_9	x_1	x_1	x_4	x_1	x_1	x_9
	Obstacle level (%)	9.70	6.75	6.30	7.67	7.87	8.12	9.09	6.63	8.03
Hebei	Obstacle factor	x_{11}	x_1	x_1	x_1	x_1	x_1	x_1	x_1	x_9
	Obstacle level (%)	8.88	6.44	6.44	7.58	7.89	7.41	8.48	5.88	6.88

Source: Authors' processing.

(2) Analysis of Obstacle Factors for Continuous Innovation Capability

Regarding the dimension of sustainable innovation capability, the primary obstacle factors affecting the evolutionary sustainability of the high-tech enterprise innovation ecosystem in the Beijing–Tianjin–Hebei region exhibit significant regional differences, as shown in Table 6. Compared to Tianjin and Hebei, Beijing

has relatively prominent advantages in sustainable innovation capability. In the early stage, Beijing's main obstacle was the full-time equivalents of R&D personnel. After 2017, this shifted to the proportion of the product export value to the total commodity export value, indicating a slight imbalances in this dimension. For Tianjin and Hebei, however, the obstacle factors and their evolutionary patterns are identical. During the 2016-2021 period, the primary obstacle was expenditure on new product development. In 2015 and 2022, this transitioned to the number of valid invention patents, revealing relatively weak sustainability in these two areas. This finding is related to the low contribution of fiscal science and technology expenditure in Tianjin and Hebei within the symbiotic evolution dimension. To enhance the sustainable innovation capability of their innovation ecosystems, both regions should strengthen their investment in technology R&D and funding allocation.

Table 6. Main obstacles to sustained innovation capability

Area	factor	2015	2016	2017	2018	2019	2020	2021	2022	2023
Beijing	Obstacle factor	x ₁₄	x ₁₄	x ₁₈	x ₁₈	x ₁₈	x ₁₈	x ₁₈	x ₁₈	x ₁₈
	Obstacle level (%)	2.93	--	2.61	1.11	0.17	--	--	--	--
Tianjin	Obstacle factor	x ₁₇	x ₁₅	x ₁₅	x ₁₄	x ₁₅	x ₁₅	x ₁₅	x ₁₇	x ₁₆
	Obstacle level (%)	5.75	7.72	6.72	6.52	7.31	6.97	8.07	7.96	7.31
Hebei	Obstacle factor	x ₁₇	x ₁₅	x ₁₅	x ₁₄	x ₁₅	x ₁₅	x ₁₅	x ₁₇	x ₁₅
	Obstacle level (%)	5.90	7.86	6.70	6.75	7.84	7.20	8.17	8.49	7.98

Note: "--" indicates that the obstacle level in the three provinces and cities in the current year is 0.

Source: Authors' processing.

(3) Analysis of Obstacle Factors in Open Innovation Vitality

Regarding the dimension of open innovation vitality, the main obstacles to the sustainable development of the innovation ecosystem of high-tech enterprises in Beijing, Tianjin, and Hebei show exhibit both notable differences and significant similarities, as shown in Table 7. For Beijing, the primary obstacle factor is the import and export trade in high-tech products, which has remained unchanged and accounts for a relatively high proportion of obstacles. In Tianjin, before 2018, the main obstacle was the output of technology transactions in the technology market. In 2019 and 2020, it shifted to expenditure on technology introduction. For Hebei, the primary obstacle factor is the import and export trade of high-tech products, with the expenditure on technology introduction being the obstacle only 2020 and 2023. Thus, Beijing and Hebei are primarily affected by the import and export trade of high-tech products, while Tianjin is affected by the turnover of technology exports and the expenditure on technology introduction in the technology market. Across the three regions, the impact of high-tech product import and export trade on open innovation vitality is substantial, which may be related to the global political and technological landscape of economic and trade competition between China and the United States over the past decade.

Table 7. Main obstacles to the vitality of open innovation

Area	factor	2015	2016	2017	2018	2019	2020	2021	2022	2023
Beijing	Obstacle factor	x_{22}	x_{22}	x_{22}	x_{22}	x_{22}	x_{22}	x_{22}	x_{22}	x_{22}
	Obstacle level (%)	28.18	47.43	54.04	41.18	29.09	27.40	31.27	27.78	27.38
Tianjin	Obstacle factor	x_{24}	x_{24}	x_{24}	x_{24}	x_{20}	x_{20}	x_{24}	x_{24}	x_{24}
	Obstacle level (%)	8.82	7.71	7.45	7.45	8.51	8.70	7.24	6.56	6.83
Hebei	Obstacle factor	x_{22}	x_{22}	x_{22}	x_{22}	x_{22}	x_{20}	x_{22}	x_{22}	x_{20}
	Obstacle level (%)	8.03	8.17	9.44	8.90	8.77	8.63	8.83	8.86	8.31

Source: Authors' processing.

6. Conclusions

Based on the relevant indicator systems and data for Beijing, Tianjin and Hebei, and employing the entropy weight TOPSIS evaluation model, this study measured the comprehensive sustainable development of enterprise innovation ecosystems in the three regions. Furthermore, the obstacles to sustainable development were analysed, leading to the following conclusions:

(1) Beijing achieved high evaluations across all three secondary dimensions of evolutionary sustainability for its high-tech enterprise innovation ecosystem, demonstrating balanced development and ranking first overall. Tianjin ranked second, while Hebei ranked third. However, within the symbiotic evolution level dimension, Hebei scored higher than Tianjin, a phenomenon potentially attributable to Hebei's larger industrial carrying capacity and resource allocation space associated with its vast hinterland. Temporally, Beijing consistently maintained a high level of sustainable development, whereas Tianjin exhibited a declining trend. Meanwhile, Hebei progressively narrowed the gap with Tianjin over time.

(2) Across the three secondary indicator dimensions, the primary obstacles to the sustainable development of high-tech enterprise innovation ecosystems in Beijing, Tianjin, and Hebei exhibit notable differences and similarities in both temporal and geographic spatial terms. Notably, during most of the study period, the obstacle factors in Tianjin and Hebei showed similar results and trends, which is consistent with the overall level of sustainable development of their innovation ecosystem. To enhance the sustainable development level of their enterprise innovation ecosystem evolution, Tianjin and Hebei should prioritise indicators such as fiscal technology expenditure (x_1), new product development expenditure (x_{15}), high-tech product import and export trade (x_{22}), technology market output transaction volume (x_{24}), and technology introduction expenditure (x_{20}).

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