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Article

Research on the path of technological innovation and resource allocation optimization of state-owned enterprises from the perspective of ecological environment and biomechanics

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Abstract: In the evolving global landscape, competition among nations has increasingly centered on the allocation of innovation resources, which are crucial for enterprises to implement development strategies under supply-side reforms. The efficiency and rationality of resource allocation directly affect the innovation capacity and operational performance of enterprises. This paper examines the relationship between technological innovation and resource allocation in state-owned enterprises through the lens of the ecological environment, employing data from multiple sources and utilizing the Data Envelopment Analysis (DEA) model to assess resource allocation efficiency. The study reveals that the proportion of R&D personnel invested in enterprises in China increased significantly from 46.35% to 73.38%, while the proportion in research institutions and universities declined to 11.48% and 11.36%, respectively. These shifts underscore the growing dominance of state-owned enterprises in driving technological innovation. The findings highlight that aligning technological innovation mechanisms with ecological sustainability not only enhances innovation capabilities and competitiveness but also accelerates industrial development and contributes to the sustainable growth of the national economy.

Keywords: ecological environment; state-owned enterprise; technological innovation; resource allocation; DEA model

1. Introduction

In the era of economic globalization, global production has shifted from nation-centered structures to enterprise-focused frameworks, placing increasing emphasis on the economic performance and innovation capacity of state-owned enterprises (SOEs). Innovation resources have become central to international competition, particularly under supply-side reforms that prioritize efficient and strategic resource allocation. Effective distribution of these resources directly influences SOEs' ability to innovate and enhance operational efficiency, yet resource scarcity presents substantial challenges as many SOEs face obstacles in advancing technological innovation due to limited resources. Even among larger, resource-rich enterprises, inefficiencies in resource distribution can hinder innovation effectiveness [1–3].

To address these challenges, innovation has become a cornerstone of national development strategies, aligning with policies that enhance supply-side structural reforms and foster an environment where market mechanisms primarily drive resource allocation, with the government providing macro-level guidance [4,5]. Technological innovation in SOEs fundamentally depends on scientific and technological resources, which form the foundation of innovation activities. Consequently, sustainable development increasingly emphasizes efficient allocation across scientific, technological, economic, and societal domains. This framework supports SOEs' competitiveness within an ecological innovation structure, as countries invest in policies and research to promote technological adoption and achieve competitive advantages in science and economic sectors, while also addressing global challenges like environmental protection [6–8].Resource allocation decision-making operates at two levels: explicit strategies and implicit, embedded decisions influenced by organizational structures, regulatory frameworks, and incentive systems [9,10]. In ecological science and technology innovation, these strategies prioritize market-driven initiatives, positioning enterprises as the primary actors within an ecologically sustainable model. Guided by policy, these efforts balance environmental and economic benefits, thereby enhancing both competitiveness and sustainability. A modern economic system requires continuous, high-quality input from scientific an technological resources, which not only foster innovation but also drive broader economic and social development [11,12].

Although resource availability is vital, effective integration and rational application within an ecological framework are essential to maximize economic returns. Enterprises must establish multi-objective technological innovation systems aligned with long-term needs, not only striving for technological success but also cultivating independent innovation capabilities to maintain a competitive edge. Nonetheless, a gap persists between current achievements in ecological innovation and anticipated goals, as many innovation infrastructures remain in early stages, lacking post-establishment support and growth [13–15]. To progress, further reforms in policy, development model transformation, and the promotion of eco-industrialization are necessary to enhance resource utilization and ecological protection. SOEs should leverage the ecological environment to build innovation mechanisms suited to their operational context, which would strengthen innovation capacity and competitiveness, expedite structural optimization, and support sustainable economic growth [16,17]. In China's active supply-side structural reform context, efficient allocation of innovation resources has gained increasing attention. Objective assessments of SOEs' resource allocation capabilities can support comprehensive development, elevate international competitiveness, and foster scientific and optimized management of innovation resources. Reviewing prior research, Genin et al. (2021) examined SOE restructuring in China's high-speed rail sector, illustrating the impact of governance frameworks on technological innovation [1]. Lo et al. (2022) explored mixed-ownership reforms, underscoring the importance of state ownership in driving innovation within restructuring efforts [2]. Additional studies highlight the roles of market mechanisms, institutional influences, and cultural factors in optimizing resource allocation across different regions and ownership structures [3,5,7].

This paper emphasizes the necessity of balanced resource allocation strategies within SOEs to foster innovation and competitiveness. Drawing on previous studies across multiple levels of innovative resource allocation efficiency, this paper proposes an innovation system based on ecological principles of "symbiosis" and "coordination", positioning regional innovative enterprises at the core, with collaboration as a fundamental goal. This approach seeks to integrate economic, ecological, and social benefits through shared technological innovation. The study assesses success rates and economic outcomes of technological innovation across various enterprise scenarios, providing insights into resource allocation strategies. Moreover, the paper outlines pathways to enhance technological innovation and resource allocation, emphasizing the importance of government-supported environmental innovation platforms that connect universities, research institutions, and market mechanisms to foster collaborative innovation [18–20].

2. Research method

2.1. Effective allocation and integration of resources in the process of technological innovation of state-owned enterprises

Technological innovation in enterprises refers to the research and development of new products and the allocation of resources for new services through innovative knowledge and advanced technologies, ultimately aimed at maximizing economic benefits. Typically, the process of technological innovation and resource allocation within enterprises can be divided into two stages. The initial stage involves knowledge production, where existing resources are transformed into new technologies and knowledge through research and development activities. In this phase, enterprises often exhibit a low degree of internationalization in production and marketing, with limited product offerings entering foreign markets [20,21]. Currently, there is a lack of systematic research comparing innovation efficiency across enterprises with different ownership structures and industry types. Additionally, an evaluation of the rationality of innovation resource allocation within state-owned enterprises (SOEs) is yet to be thoroughly established. To address these issues, recommendations include improving the governance mechanisms of high-tech listed companies by increasing the proportion of independent directors, particularly those with technical expertise. Further, implementing a leadership model that combines the roles of chairman and general manager can provide management with greater autonomy in innovation.

Optimizing the incentive structures for enterprise management is also critical. This includes integrating monetary compensation for managers with equity-based incentives and increasing the role of equity incentives within the broader incentive framework. Under an innovation-driven development strategy, and while maintaining control of the state-owned economy, the efficiency of SOE innovation should be a key consideration in resource allocation. As subsidiaries and branches acquire knowledge on advanced technologies through relevant activities, they transmit essential information back to corporate headquarters and corresponding innovation centers, thereby supporting cohesive and informed innovation across the organization.

In essence, the decomposition of comprehensive efficiency is to use distance function to express the index of comprehensive efficiency change. Considering the availability of data and the non quantifiable nature of some factors, only enterprise scale, enterprise performance, year and industry are selected as control variables, and the control variable enterprise growth is added in the robustness test [22]. However, the factors affecting the technological innovation of listed companies are far more than these. There are also government subsidies, policy environment and so on. We can consider introducing these factors to control them. The intertemporal change of resource allocation of comprehensive efficiency can be derived from the change of production technology or the change of technical efficiency. If the production technology is used, the comprehensive efficiency can be decomposed into several changes from different sources. Based on the output oriented approach, the source of comprehensive efficiency can be further divided into two parts: scale efficiency and congestion:

$$TE_O = \frac{D_{OC}^t(y_t, x_t)}{D_{OC}^s(y_s, x_s)} \tag{1}$$

Among them, TE_O is the scale efficiency based on output orientation, while C_O is the crowding degree based on output orientation.

The effectiveness of the evaluation after the weighting is not affected, that is, the evaluation of the model and the weighted model as effective is the same, but the invalid efficiency value and its projected value will change.

$$min\,\rho = \frac{\sum_{i=1}^{m} \omega_I}{1 + \sum_{r=1}^{q} \omega_r} \tag{2}$$

where, ω_I and ω_r represent the weights of input and output indicators.

The outputs of technological innovation and resource allocation of enterprises are also divided into two categories. One is the intermediate output, that is, the scientific and technological achievements of technical knowledge, which represents the level of knowledge output of enterprises and is mainly expressed by the amount of effective invention patents authorized by enterprises; The other is the economic benefit category, that is, the final output, which mainly converts the existing R & D achievements into market-oriented new products and ultimately obtains economic benefits from resource allocation. It represents the commercialization level of innovation achievements and is usually measured by the sales income of new products. Corporate governance includes internal governance and external governance. The internal governance mechanism only considers the equity structure, the board structure and the management incentive, and does not consider the board of supervisors structure. The external governance mechanism only considers the control market, debt constraint and product market, and does not involve the manager market, institutional investors, government, suppliers and other stakeholders. However, compared with the investment status of Chinese enterprises in international innovation, the current investment scale is still too small.

2.2. Technological innovation and resource allocation improvement path of eco-enterprises

The innovation achievements of state-owned enterprises, along with resource allocation transformation and industrial development, constitute a systematic project that involves various elements, including demand identification, technology adoption, talent alignment, financial support, and market promotion. Third-party service providers in the market typically focus on only one or two of these aspects, thus lacking the capacity to provide comprehensive, life-cycle support for innovation projects. Therefore, building an innovation platform that aggregates diverse services and resources is essential to create a cluster effect. The external governance mechanism significantly impacts enterprise technological innovation. For example, moderately increasing the proportion of unrestricted shares can intensify capital market pressures on executives, motivating them to enhance enterprise value through technological innovation as an anti-takeover measure. In state-owned enterprises, the technological innovation and resource allocation process is guided by the principles of sustainable economic development, integrating ecological concepts. This approach, led by government guidance, with innovative enterprises as the carriers and universities and research institutions as collaborators, strengthens cooperation to ensure the coordinated growth of the economy, society, and natural environment in a sustainable, circular fashion.

Enterprise resource allocation involves distributing various economic resources by quality and quantity across economic fields to gain competitive advantage and develop a strategic framework. In this context, allocating innovative resources—such as manpower, materials, finances, and information—is vital for enhancing enterprise innovation capabilities and regional competitiveness. The enterprise innovation system is a complex network with enterprises as power sources, universities and research institutions as knowledge bases, intermediary services as bridges, and government as a regulatory force. These entities interact and rely on each other, with the shared goal of advancing sustainable technological innovation, exhibiting characteristics of integrity, dynamism, openness, and hierarchy. Research on the efficiency of state-owned enterprises' innovation resource allocation should extend beyond the system itself. Adjusting the allocation of SOEs' innovation resources is a strategic approach to improving the overall innovation efficiency of the state-owned economy. Compared with most enterprises, SOEs have made considerable progress in innovation internationalization, featuring relatively large-scale operations and comprehensive systems. As the link between technology, resource allocation, and economic growth, enterprise technological innovation remains subject to institutional constraints, especially when transforming new technologies into commercial ventures for economic advancement. The substantial financing available in the market meets the significant capital needs of high-tech enterprises for R&D and innovation, particularly benefiting small and medium-sized board and GEM high-tech enterprises. This financing lowers the debt ratio within the capital structure, mitigates the adverse effects of debt constraints, and ultimately generates higher returns for shareholders. Creating a standardized resource allocation system aligned with the ecological environment for technological innovation is essential for the commercialization and prosperity of technological achievements. However, from a resource acquisition and allocation perspective, resource flows between headquarters and overseas branches remain predominantly unidirectional.

Considering the public welfare of environmental protection and the strong policy driven characteristics of the ecological environment science and technology innovation system, the establishment of the environmental innovation platform can not be separated from the participation and guidance of the government. It is a construction path that can be tried that the government sets up the platform, universities and research institutions introduce technical resources, operate according to the market mechanism, and develop towards the third-party platform. It includes the technological innovation ability of the innovation subject, the ecological innovation platform and the ecological innovation environment. All innovation subjects in the ecological environment of technological innovation and resource allocation of state-owned enterprises take the ecological innovation environment as the guarantee and the ecological innovation platform as the cooperative way to carry out collaborative innovation and achieve the goal of technological innovation resource allocation. Calculate the proportion w of the scientific and technological resources of each group of industrial enterprises in the total scientific and technological resources of industrial enterprises and the proportion P_i of the number of regions, then the calculation formula of the Gini coefficient of the location is:

$$G = 1 - \sum_{i=1}^{n} P_i \times Q_i = \sum_{k=1}^{i} w \tag{3}$$

The concentration rate is mainly used to measure the contribution of each index to the overall gap, and the calculation formula is:

$$G_j = 1 - \sum_{i=1}^{n} P_i \times j = 1,2,\ldots,m \tag{4}$$

The calculation formula of c_j contribution rate is:

$$C_j = Y_j \times G_j \Sigma_{j=1}^{n} \tag{5}$$

Among them, w is the proportion of the j index in i area to the j index in the total scientific and technological resources of industrial enterprises.

On this basis, the total intra-group gap G_A is calculated by the following formula:

$$G_A = \sum_{i=1}^{3} W_i P_i \tag{6}$$

Finally, the overlapping coefficient G_O between groups is obtained, and the calculation formula is:

$$G_O = G - G_A - G_B \tag{7}$$

The profit function of the enterprise is expressed as:

$$\pi = PY - E + I_E \tag{8}$$

Among them, E and I_E are the capital prices of enterprises with and without ecological innovation respectively.

The enterprise optimization behavior is expressed as:

$$max(PY - E + I_E - r_l K_E) \tag{9}$$

PY means the upper limit of environmental regulation, that is, the maximum amount of pollutants discharged by the government.

The optimization conditions should meet:

$$\frac{\partial l}{\partial \lambda} = B(Y, E) \tag{10}$$

The above is to analyze the impact of different environmental regulations on enterprise ecological innovation.

The allocation efficiency of innovation resources among regions or industries is still very low, and the input of innovation resources in some regions and industries is relatively redundant. Reasonable adjustments should be made according to the specific situation of innovation resources allocation in different regions and industries to improve the allocation efficiency of innovation resources. In the process of internationalization of technological innovation, state-owned enterprises should expand technological information channels and make use of a wider range of resources to allocate information sources. In addition to conventional sources of innovation, such as the company's internal, market, customers, suppliers, sellers and competitors, state-owned enterprises should pay attention to some low-cost technical information sources that are more suitable for China's current situation, including the most convenient and inexpensive public information sources. By analyzing the essential characteristics of environmental technology and mining more resource allocation technologies associated with it, environmental technology can be innovated and developed rapidly. At present, there is a lack of institutions in China that can really identify and judge environmental technologies, let alone dig deep into the source of technological innovation through application demand side to promote major breakthroughs.

3. Results analysis and discussion

This experiment examines the distribution of R&D personnel across three main innovation entities: Enterprises (a), scientific research institutions (b), and universities (c). In 2014, Chinese R&D personnel within industrial enterprises above a designated scale invested a total of 697,000 person-years, representing 46.35% of total R&D personnel. Scientific research institutions accounted for 232,000 person-years (15.39%), and universities accounted for 243,000 person-years (16.12%). These data indicate that the majority of China's R&D personnel are concentrated in enterprises, with research institutions and universities comprising relatively smaller shares.

Notably, by 2018, the proportion of R&D personnel in enterprises had risen from 46.35% to 73.38%, while the shares in scientific research institutions and universities decreased from 15.39% to 11.48% and from 16.12% to 11.36%, respectively. This shift reflects the strengthening of the dominant role of state-owned enterprises in China's innovation landscape. **Table 1** and **Figure 1** illustrate the allocation of Chinese R&D personnel among these innovation entities from 2014 to 2021.

Table 1. Allocation of Chinese R&D personnel in different innovation entities from 2014 to 2021.

Particular year	Full time equivalent of R&D personnel	Enterprise	Percentage of enterprises	Scientific research institution	Percentage of scientific research institutions	Colleges and universities	Percentage of Universities
2014	50.28	69.7	46.35%	23.2	15.39%	24.3	16.12%
2015	73.63	85.9	49.43%	25.6	14.70%	25.5	14.64%
2016	96.55	101.5	51.61%	26.1	13.24%	26.7	13.55%
2017	29.14	144.8	63.17%	27.8	12.11%	27.6	12.01%
2018	55.39	187.40	73.38%	29.4	11.48%	29.1	11.36%
2019	88.31	193.8	67.27%	31.7	10.97%	29.8	10.38%
2020	24.69	225.7	69.18%	34.5	10.62%	31.5	9.68%
2021	53.29	250.5	70.60%	36.5	10.31%	32.6	9.21%

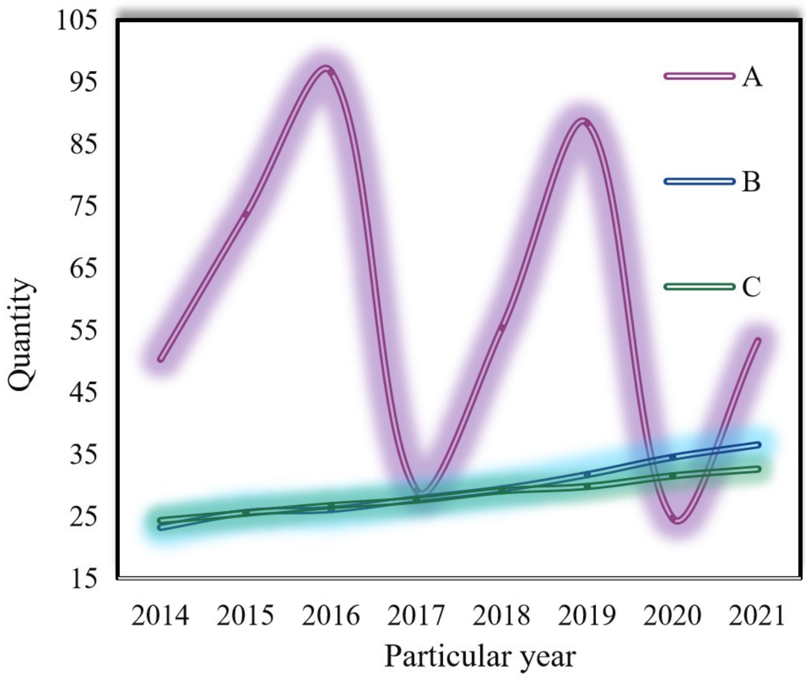

Figure 1. Allocation of Chinese R&D personnel in different innovation entities from 2014 to 2021.

From the perspective of different activity subjects, this experiment examined three categories: Enterprises (A), scientific research institutions (B), and universities (C). In total, various enterprises spent 1214.4 billion yuan, accounting for 44.15%, 17.96%, and 13.61% of the expenditures for enterprises, government research institutions, and universities, respectively. From 2014 to 2021, the internal expenditure of China's R&D funds by scientific research institutions and higher education institutions showed a declining trend, dropping from 18.88% to 15.06% and from 9.23% to 7.24%, respectively. Conversely, the internal R&D expenditure invested in enterprises has risen from 71.09% to 76.62%.

These trends indicate that enterprises are increasingly becoming the primary drivers of China's innovative resource allocation, while the proportion of R&D resources allocated to universities and research institutions is steadily decreasing.

Table 2 and **Figure 2** display the internal expenditure allocation of China's R&D funds across these entities from 2014 to 2021.

Table 2. Internal expenditure allocation of R&D funds in China from 2014 to 2021.

Particular year	Internal expenditure of R&D funds	Enterprise	Proportion	Scientific research institution	Proportion	Colleges and universities	Proportion
2014	3003.12	2134.51	71.09%	567.31	18.88%	276.81	9.23%
2015	3710.25	2681.92	72.29%	687.92	18.55%	314.72	8.49%
2016	4616.03	3381.71	73.27%	811.31	17.59%	390.22	8.54%
2017	5802.12	4248.62	73.24%	995.91	17.17%	468.23	8.08%
2018	7062.59	5185.51	73.43%	1186.42	16.81%	597.31	8.47%
2019	8687.02	6579.31	75.75%	1306.71	15.05%	688.91	7.94%
2020	10,298.42	7842.22	76.16%	1548.91	15.05%	780.61	7.59%
2021	11,846.63	9075.81	76.62%	1781.42	15.06%	856.72	7.24%

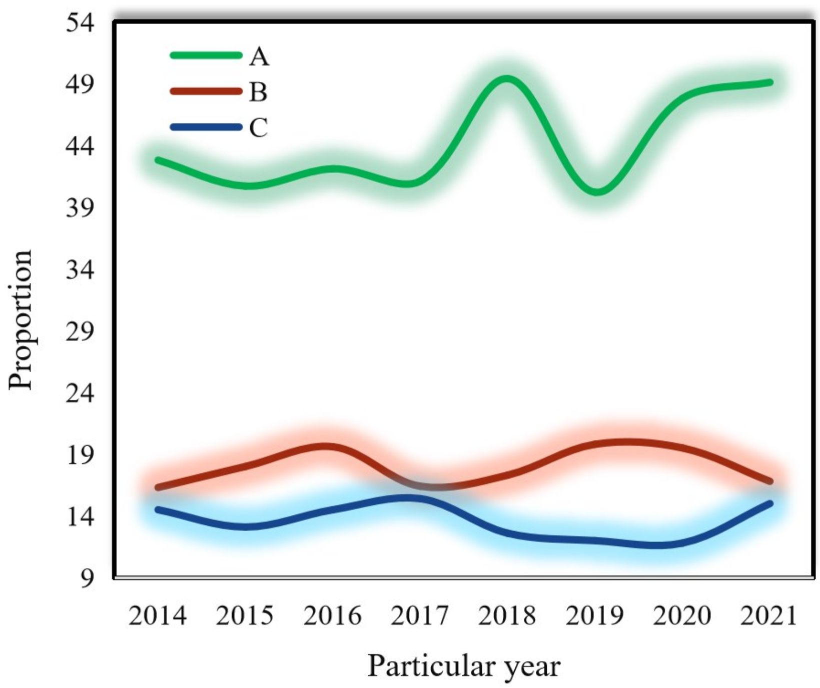

Figure 2. Internal expenditure allocation of R&D funds in China from 2014 to 2021.

In 2021, the full-time equivalent of China's R&D personnel was highest in Jiangsu, followed by Zhejiang and then Beijing. Jiangsu also led in research personnel input, with Beijing in second and Zhejiang in third place. For experimental development investment, Jiangsu ranked first, followed by Zhejiang and Beijing. These data indicate that Jiangsu, Zhejiang, and Beijing possess abundant innovative human resources, while regions such as Hebei and Shanghai have relatively fewer innovation-driven human resources. The distribution of R&D personnel across different regions in China in 2021 is presented in **Table 3** and **Figure 3**.

Table 3. Allocation of Chinese R&D personnel in different regions in 2021.

Region	Full-time equivalent of R&D personnel	Researchers	Fundamental research	Application research	Experimental development
Beijing	253,339	150,575	46,338	63,695	143,307
Hebei	111,385	50,344	6209	15,829	89,350
Shanghai	183,933	92,864	20,681	23,561	139,693
Jiangsu	543,439	201,378	16,918	28,641	497,981
Zhejiang	376,554	120,288	8899	15,545	352,113

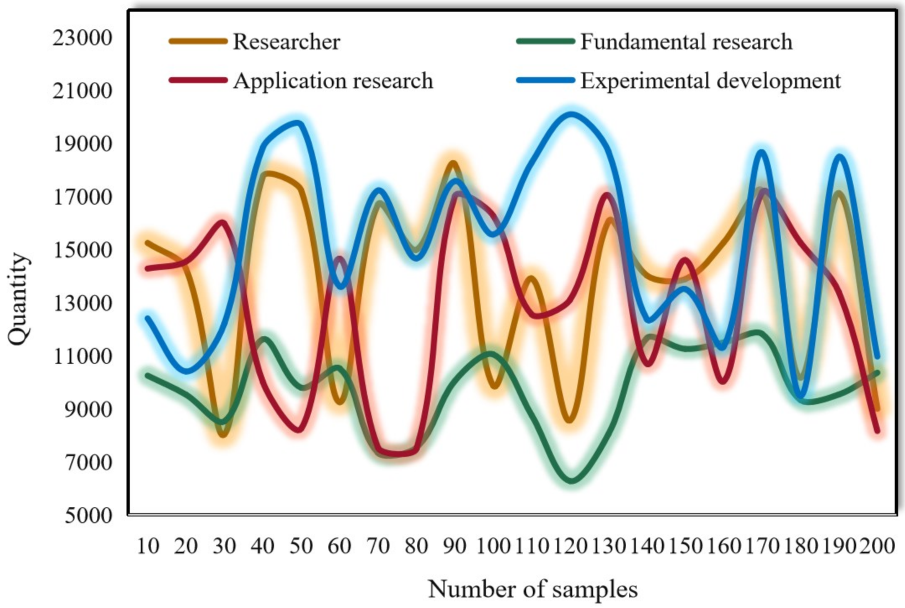

Figure 3. Allocation of R&D personnel in China in 2021.

Both substantive ecological innovation and strategic ecological innovation by enterprises have shown an upward trend over the years, indicating a continuous improvement in the level of ecological innovation among Chinese enterprises. However, examining the structure of ecological innovation reveals that the number of substantive ecological innovations is not significantly higher than that of strategic ecological innovations. In certain years, the number of strategic ecological innovations even exceeds that of substantive ecological innovations, as illustrated in **Figures 4** and **5**.

Figures 4 and **5** indicate that the number of innovations is highest in the eastern region, followed by the central region, and lowest in the western region. The eastern economic belt benefits from a favorable geographic location and has been prioritized by national policies, which has attracted a steady influx of capital, labor, and technology. As a result, factors such as foreign direct investment (FDI), industrial structure, and resource and energy management in the eastern region have been continuously optimized, fostering enterprise ecological innovation. Although ecological innovation levels in the central and western economic belts are comparatively lower, they have steadily improved due to the influx of capital and advanced technology driven by the "Rise of Central China" and "Development of Western China" strategies.

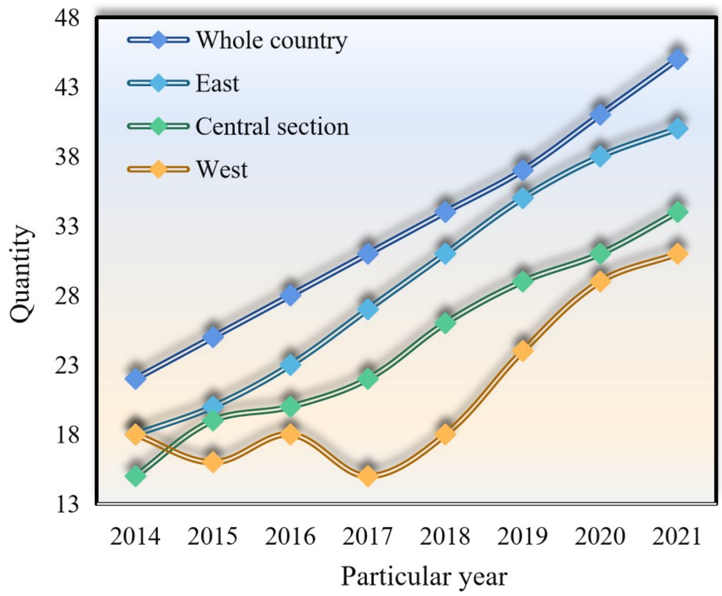

Figure 4. Number of substantial ecological innovations of enterprises.

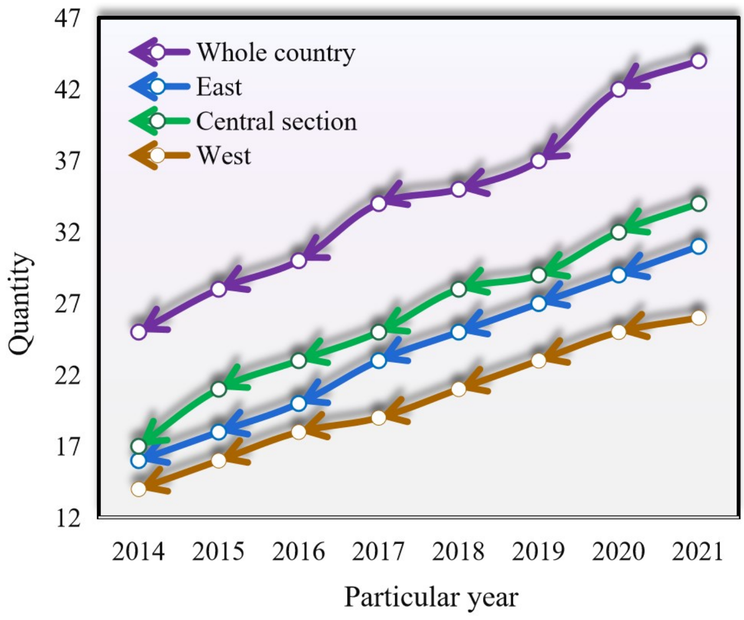

Figure 5. Number of strategic ecological innovations of enterprises.

4. Conclusions

With the enhancement of management capabilities and R&D innovation within state-owned enterprises (SOEs), a positive correlation has been observed between product market competition and technological innovation investment in SOEs, though this relationship is less significant in non-state-owned enterprises. Additionally, the corporate governance index shows a strong positive correlation with technological innovation investment. This paper examines the technological innovation and resource allocation of SOEs through an ecological environment perspective. Findings indicate that the proportion of R&D personnel invested in enterprises in China has risen significantly, from 46.35% to 73.38%, while the share in scientific research institutions and universities has decreased from 15.39% to 11.48% and from 16.12% to 11.36%, respectively, establishing SOEs as dominant players in China's innovation landscape. Although SOEs still exhibit lower innovation efficiency compared to other ownership types, innovation efficiency is gradually improving across all types of enterprises, with SOEs showing the most rapid progress.

At present, technology identification in the field of ecological and environmental technology remains underdeveloped, offering opportunities for enhancement. Strengthening this area can facilitate better understanding and adoption of innovative technologies among technology users. In assessing the innovation efficiency of SOEs within the ecological context, a balanced view is essential. Rather than being overly critical of SOEs as they work to improve their innovation efficiency, it is important to recognize the broader social responsibilities they bear. Greater support and encouragement will enable SOEs to advance their innovation capabilities, ultimately contributing positively to sustainable development goals and societal welfare.

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Conflict of interest: The author declares no conflict of interest

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