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The Impact of Integration Between Innovation Chain, Industrial Chain, and Talent Chain on Urban Carbon Productivity: Evidence from China

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Abstract

In the new stage of development, promoting the integration of "industry-innovation- talent chains" is an important measure to achieve low-carbon transformation and development in cities. This study analyzes the internal logic of the integration of "industry-innovation-talent chains" from the perspective of triple helix theory. Based on panel data from 281 cities from 2003 to 2021 in China, the composite system synergy model is used to measure the degree of the integration of "three chains", and identify the comprehensive impact and mechanism path of the integration of "three chains" on urban carbon productivity. The results show that the integration of "three chains" significantly improves urban carbon productivity, and this conclusion still holds true after a series of robustness tests. The heterogeneity analysis results indicate that the integration of "three chains" has a more positive impact on carbon productivity in low-carbon pilot cities, new energy demonstration cities, non resource based cities, and innovative cities. Mechanism testing shows that the integration of "three chains" indirectly improves urban carbon productivity by enhancing industrial agglomeration, promoting technological innovation and optimizing energy structure. The research has expanded the application boundaries of the integration of "three chains" and provided policy insights for improving urban carbon productivity through the integration of "three chains".

Keywords: integration of "industry-innovation-talent chains"; urban carbon productivity; collaboration degree of composite system; triple helix theory

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1. Introduction

To build a modern socialist country in all respects, we must, first and foremost, pursue high-quality development. The report of the 20th National Congress of the Communist Party of China pointed out that a green and low-carbon economy and society are crucial to high-quality development. In the context of accelerating the implementation of the innovation driven development strategy, the coordinated promotion of two major development tasks of growth and carbon reduction, and the realization of green economic transformation and development are major practical problems that China urgently needs to solve today (Liu & Sun, 2023). According to the BP World Energy Statistical Yearbook 2022, China's carbon emissions are 10.87 billion tons, accounting for 32.07% of global total. Therefore, carbon reduction is facing enormous pressure for China. Improving carbon productivity is not only an inherent requirement for the development of a low-carbon economy, but also a primary choice to achieve peak carbon emissions around 2030 in China. During the second collective study session of the Political Bureau of the Communist Party of China Central Committee in January 2023, General Secretary Xi Jinping emphasized that we must adhere to the integrated deployment of innovation chain, industry chain, talent chain (hereinafter referred to as "three chains"), and promote deep integration. The integration of industry chain and innovation chain is an important driving force for promoting the transformation and development of low-carbon economy (Li et al., 2023), and the supporting role of talent chain in the integration of industry chain and innovation chain has attracted academic attention (Zhao et al., 2023). So, what is the theoretical logic and impact mechanism of "three chains" integration on carbon productivity? The exploration of this issue not only helps to form a new perspective for identifying factors affecting carbon productivity, but also has certain theoretical and practical significance for promoting the low-carbon transformation and development of cities.

2. Literature Review and Theoretical Hypotheses

2.1. Literature Review

Although there is a lack of theoretical and empirical evidence on the impact about the integration of "three chains" on carbon productivity, existing achievements still provide important references for this study. There are three main sources of relevant literature: The first is the development of "single chain" or "double chain" coupling research. The academic research on "single chain" mainly focuses on the definition of connotation and implementation path, while the exploration of "double chain" is not limited to the connotation characteristics and integration path. The quantitative research results on the degree of integration of "double chain" are gradually becoming more abundant, which helps to further analyze its temporal and spatial characteristics and economic impact effects. The second literature is the specific practice of integrating "three chains" in talent evaluation, industry, and livelihood issues, among which the talent chain and the capital chain are listed as key elements in integrating into the innovation chain and industry chain. On the one hand, after the integration of talent chain into "industry-innovation chains", it is possible to analyze the evaluation and optimization of talents in urban agglomerations. On the other hand, some scholars have pointed out that there is a significant gap compared to developed economies in the integration of "industry-innovation-capital chains" in China's integrated circuit. A case study based on the integration theory of industry-supply- -value chains" shows that the development of rural e-commerce can empower the employment and income increase of reservoir immigrants. The third literature is an analysis of the influencing factors on carbon productivity. Non policy factors include value chain embedding, environmental regulations, digital economy, and factor inputs, while policy factors include financial reform, carbon trading, and the "Broadband China" pilot policy. Table 1 summarizes the literature review situation.

Table 1. Literature review on "three chains" and carbon productivity.

Key Word	Research Object	Key Content	Representative Scholar
Single Chain	Industry Chain	Connotation, Characteristics	Sheng(2019)
	Innovation Chain	Connotation, Theoretical System	Chen et al.(2025)
Double Chains	Industry Chain,Innovation Chain	Connotation, Path, Characteristics, Influencing Effects	Hu(2020), Gao(2022), Yu et al.(2024), Li & Gong(2021)
	Industry Chain,Talent Chain	Coupling Development	Jiang & Zhang(2022)
	Innovation Chain, Talent Chain	Diversified Integration Path	Zhang et al.(2024)
Three Chains	Industry-Innovation-talent chains	Talent Policy Evaluation	Dong et al.(2024)
	Industry-Innovation-Capital Chains	Collaborative Development of Integrated Circuit Industry	Sun & Liu(2023)
	Industry-Supply- Value Chains	Reservoir Resettlers' Employment and Income Growth	Zeng et al.(2023)

Carbon Productivity	Non Policy Factors	Value chain embedding, High-tech Industry Agglomeration, Digital Economy	Sun & Du(2020), Yang et al.(2021), Wu & Deng(2023), Zhao et al.(2022)
	Policy Related Factors	Western Development Strategy, Financial Reform Pilot Zone Policy, Carbon Trading Policy, “Broadband China” Pilot Policy	Zhang et all(2022), Liu & Sun (2022)，Fang & Li(2023), Cao &Peng(2024)

Regarding the research on the integration of “three chains” and carbon productivity, although existing literature has achieved certain results, laying a good foundation for further exploring the relationship between them, there is still room for further expansion. In terms of research perspective, few scholars have identified the influencing factors of carbon productivity based on the specific perspective of “three chains” integration. In terms of theoretical research, scholars have explored the problem of “double chain” fusion using the double helix model (Xu & Zhang, 2023). Due to the late start of academic attention to talent chain, the logical exploration of the integration of “three chains” is still insufficient, and a systematic theoretical analysis framework has not yet been formed. In terms of quantitative research, most existing scholars have measured the coupling coordination degree of “double chain” at the provincial level (Li & Gong, 2021). Due to the scarcity of scholars evaluating the degree of integration of “three chains”, thus giving rise to the lack of empirical evidence at the urban level, there is relatively little literature on the impact of “three chains” integration on the low-carbon transformation and development of cities.

In response to the aforementioned research gaps, this study examines the impact of the integration of “three chains” on urban carbon productivity based on panel data from 281 cities in China from 2003 to 2021. There may be three innovative points in this study. Firstly, in terms of research perspective, incorporating the integration of “three chains” into the same analytical framework as urban carbon productivity not only deepens the identification of influencing factors on carbon productivity, but also expands the comprehensive impact and internal mechanism of the “three chains” integration on urban carbon productivity. Secondly, in terms of theoretical analysis, using the triple helix theory to explain the integration of “industry-innovation-talent chains”, making up for the current lack of core research and limited theoretical progress in the integration of “three chains”. Finally, in terms of practical value, the composite system coordination model is used to measure the degree of “three chains” integration, helping explore the characteristic trends and impact effects of integration of “three chains” at the urban level, thus providing policy insights for promoting the deep integration of “industry-innovation-talent chains” , and achieving low-carbon transformation and development for cities in China.

2.2. Theoretical logic

Industry chain emphasizes the extension of the value chain, which covers the entire process of producing products or providing services, and it is the unity of industrial organization, production process, and value realization (Huang & Ni, 2020). Innovation chain is the refinement and adaptation adjustment of innovation clusters, innovation networks, innovation ecosystems, and innovation systems (Chen et al., 2024). Talent chain is a chain of talent aggregation formed by the transmission and correlation of industrial knowledge, skills, achievements, experience, etc(Nie et al., 2024). The essence of the integration of “industry-innovation-talent chains” is the effective allocation of resources such as innovation and talent. Generally speaking, the industry chain connects various industrial nodes, enabling the smooth operation of the industry chain. The innovation chain constantly stimulates new knowledge and creativity at the nodes of the industry chain, driving the entire industry chain forward. The talent chain gathers outstanding talents from various industries, providing continuous sources of power for the extension of the industry chain and the prosperity of

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the innovation chain. Therefore, the integration of "three chains" means that a new development pattern of synergy, complementarity, and overall optimization has been formed among industries, technology, and talents.

The triple helix theory proposed by Etzkowitz (2003) provides a theoretical basis for the fusion of "three chains" (Zeng et al., 2023). The integration of "industry-innovation-talent chains" is reflected in the multi-directional promotion of the three, forming a complementary positive feedback loop and a stable triple helix structure. On this basis, this study constructs a theoretical analysis framework for the integration of "industry-innovation-talent chain". Firstly, integration of industry chain and innovation chain has achieved a positive interaction between industrial development and innovation resources, forming a closed loop of "industry-innovation chains". On the one hand, as the soil and foundation of innovation chain, the industry chain provides direction, goals, and financial support for cultivating the innovation chain. On the other hand, embedding the innovation chain into various nodes of the industry chain not only helps to solve "bottleneck" technical problems in the process of industrial development, but also enhance the resilience and stability of industry chain. Secondly, the integration of innovation chain and talent chain has achieved resonance between technological innovation and talent drive, forming a closed loop of "innovation-talent chains". The core driving force for innovative development is actually talent, and the essence of technological competition is talent competition. Therefore, the creativity generated by the talent chain is the core driving force for the development of the innovation chain. At the same time, the development of the innovation chain provides more career development opportunities for talents, attracting and retaining more outstanding talents. Once again, the integration of industry chain and talent chain has achieved a two-way promotion of industrial prosperity and talent aggregation, forming a closed loop of "industry-talent chains". Industry is an important carrier for talent aggregation, and talent is an important driving force for industrial prosperity (Liu, 2024). On the one hand, the talent chain promotes the development of the industry chain through knowledge spillover and complementary factors, supporting the smooth operation of various links in the industry chain. On the other hand, a sound industry chain means a successful feedback to the talent chain by promoting talent aggregation and further improving the quality and quantity of talent. Therefore, the theoretical logic of "industry-talent chains" integration can be summarized as a triple helix structure formed by the closed-loop of "industry-innovation chains", "innovation-talent chains", and "industry-talent chains" (Zhao et al., 2023).

2.3. Theoretical Hypotheses

2.3.1. The Direct Impact of the Integration of "Three Chain" on Carbon Productivity

The low-carbon development model not only relies on the "carbon reduction" caused by the slowdown of economic activities, but also benefits from the "efficiency enhancement" caused by the improvement of economic efficiency (Huang & Xie, 2023). Carbon productivity is an important indicator for measuring low-carbon development. "carbon reduction" and "efficiency enhancement" are two main principles for improving carbon productivity consequently. Carbon reduction refers to reducing greenhouse gas emissions, such as carbon dioxide from the source. Efficiency enhancement not only includes increasing economic benefits, but also encompasses increasing environmental and social benefits. The environmental orientation of the integration of "three chains" not only enhances economic benefits, but also emphasizes the protection of the natural environment. Therefore, the integration of "three chains" has a significant impact on improving carbon productivity. First of all, the innovation chain is the core driving force for promoting the transformation and upgrading of the industry chain. As the demand for green and low-carbon technologies from various entities in the chain gradually increases, developing and applying low-carbon technologies, carbon emissions in the production process can be significantly reduced. The integration of industry chain is conducive to the coordinated development of upstream and downstream enterprises, realizing the circular utilization of resources, and forming a closed-loop industry chain. What's more, the sustained development of innovation chain is accompanied by technological changes and model innovations. The various entities in chains will accelerate the frequency of technological connections through spontaneous mechanisms, thereby improving total factor productivity, which is crucial for improving the production efficiency and product quality of the industry chain. The rapid development of the industry chain will generate more market demand, further stimulating the optimization and upgrading of the innovation chain. Furthermore, the improvement of the talent chain can help cultivate a group of professional talents with low-carbon awareness and mastery of green key technologies. It not only provides strong support for low-carbon development, but also provides a solid foundation for the deep integration of industry chain and innovation chain. Therefore, the accumulation of intellectual capital brought by the talent chain can generate sustained environmental competitive advantages and green economic benefits. Therefore, the integration of "three chains" helps to form a green and low-carbon development model, achieving the two main goals of "carbon reduction" and "efficiency enhancement", while promoting economic growth and balancing environmental protection. On this basis, this article proposes hypothesis:

H1. *the integration of "three chains" promotes the improvement of urban carbon productivity directly.*

2.3.2. The Indirect Impact of the Integration of "Three Chains" on Carbon Productivity

To explore the indirect impact of the integration of "three chains" on carbon productivity, this study absorbs the viewpoints of scholars about the influencing factors and transmission effects on carbon productivity(Zhang et al., 2017; Guo et al., 2023; Song et al., 2023; Song et al., 2024) . Based on the three dimensions of industry agglomeration, technology innovation, and energy structure, a "industry-technology-energy" analysis framework is constructed to analyze the indirect transmission mechanism of "three chains" integration on carbon productivity.

Depending on the guidance of the innovation chain, enterprises on the industry chain promote technological progress and mode change in the process of integrating "three chains" continuously, thus forming a positive interaction between the industry chain extending towards the innovation chain and the development of the innovation chain matching the industry chain. At the same time, the talent chain provides strong support for the deep integration of the industry chain and innovation chain, thereby efficiently integrating various resources and achieving information sharing. This mechanism of resource complementarity and sharing helps attract enterprises to gather together and form industrial agglomeration with core competitiveness. The scale effect and synergy effect brought by industrial agglomeration have a positive impact on improving carbon productivity. On the one hand, the scale effect of industrial agglomeration not only reduces the operating costs of individual enterprises, but also helps optimize resource allocation, improve resource utilization efficiency, and thereby reduce energy consumption and emissions per unit output. On the other hand, the synergistic effect of industrial agglomeration enables close cooperation between enterprises, universities and research institutions, which helps to improve overall competitiveness, reduce ineffective investment and resource waste, further promoting green and low-carbon development for cities. So this paper proposes hypothesis :

H2. *the integration of "three chains" indirectly improves carbon productivity by promoting industrial agglomeration.*

The role of "three chains" integration in promoting technological innovation is multifaceted, as they intertwine and support each other, creating an environment conducive to the development of the innovation ecosystem jointly. A complete and active industry chain provides rich practical scenarios for technological innovation. As the source and driving force of technological innovation, the innovation chain transforms scientific research achievements into market competitive products through industry university research cooperation. When the talent chain is closely integrated with the industry chain and innovation chain, talents can keenly grasp market demand and innovation

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direction, thus providing intellectual support for technological innovation. Currently, "greening" and "digitization" are two important trends in the new round of technological revolution and industrial transformation. On the one hand, green technology innovation can effectively promote the reduction of carbon emissions in cities (Tian & Qin, 2024), which helps to achieve coordination and balance between economic development and environmental protection. On the other hand, digital technology innovation can achieve carbon reduction by empowering the flow of various carbon elements between cities (Yu et al., 2024). While promoting high-quality economic development, it has also increased carbon productivity. So we can proposes hypothesis:

H3. *the integration of "three chains" indirectly improves carbon productivity by promoting technological innovation. Among them, green technology innovation and digital technology innovation play important transmission role.*

The integration of "three chains" has had a positive impact on optimizing the energy structure, and this integration helps to achieve a virtuous cycle of innovation chain leadership, industry chain integration, and talent chain interaction. Firstly, as the key to technology research and development and achievement transformation, the innovation chain can guide the development of more efficient and cleaner energy technologies, thereby promoting the diversified development of energy structure. Secondly, after integration and optimization of the industry chain, effective allocation of resources can be achieved, thereby reducing the consumption of fossil fuels, lowering carbon emissions from the source, and ultimately achieving energy structure transformation and upgrading. Finally, the interaction between talent chain and innovation chain makes talent cultivation aligned with technological needs more closely. The interaction between talent chain and industry chain makes green industries more dependent on human capital. This interactive relationship not only supports the sustainable innovation of energy technology, but also ensures a positive communication between industrial development and talent cultivation, thereby providing sustained impetus for optimizing the energy structure. Due to the transformation of energy structure supporting the improvement of carbon productivity (Sun & Du , 2020), this article proposes hypothesis:

H4. *the integration of "three chains" indirectly improves carbon productivity by optimizing the energy structure.*

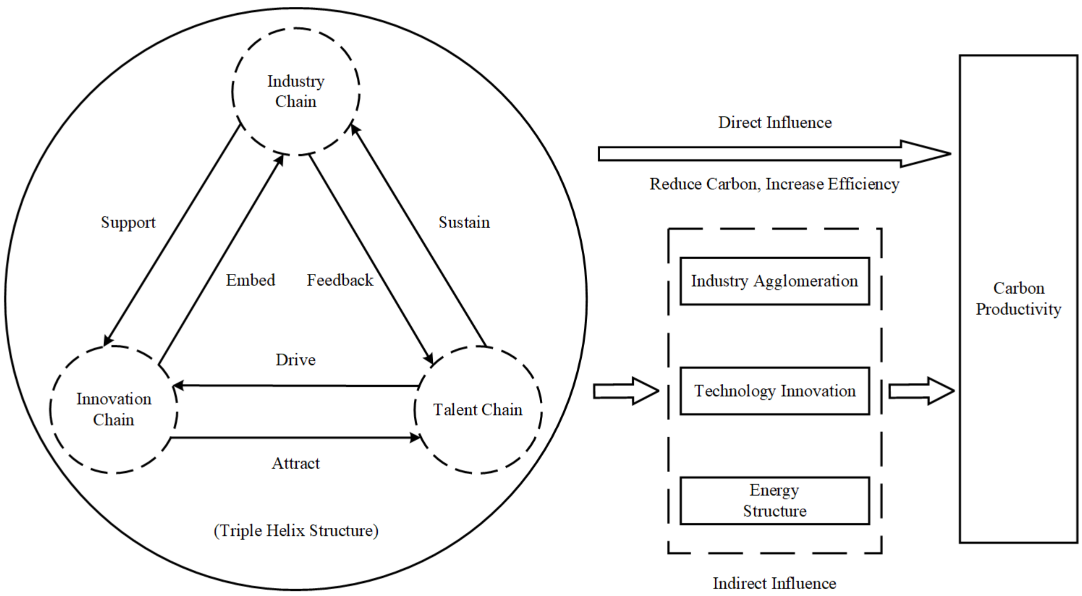

Figure 1. Theoretical framework of the impact of integration of "three chains" on carbon productivity.

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3. Materials and Methods

3.1. Model Setting

To identify the causal relationship between the integration of "three chains" and urban carbon productivity, a mathematical model is constructed with urban carbon productivity (CP) as the dependent variable, and the degree of integration of "three chains" (TID) as the core explanatory variable, combining with control variables. In equation (1), the dependent variable CP_{mt} represents the carbon productivity in city m during period t, the core explanatory variable TID_{mt} represents the degree of integration of "three chains" in city m during period t, X_{mt} represents the control variables that affects the carbon productivity in city m during period t, u_m represents the entity fixed effects that does not change over time, v_t represents the Time Fixed effect that does not change over entity, ε_{mt} represents the random disturbance term.

$$CP_{mt} = \alpha_0 + \alpha_1 TID_{mt} + \alpha \sum X_{mt} + u_m + v_t + \varepsilon_{mt} \quad (1)$$

3.2. Indicator Selection and Data Sources

3.2.1. Core Explanatory Variable

The coupling coordination degree can be used to measure the strength of the interaction between subsystems (Liu, 2021). This study draws on the methods of Wu (2021) and Han et al. (2023) to construct a composite system synergy model. The composite system formed by the integration of the industry chain, innovation chain, and talent chain can be defined as S_i={S_1，S_2，S_3}. S_1 represents the subsystem of industry chain, S_2 represents the subsystem of innovation chain , and S_3 represents the subsystem of talent chain . The order parameter of each subsystem is e_{ij}（j=1，2，…k）, where α_{ij} and β_{ij} respectively represent the upper and lower limits of the order parameter in the subsystem. As a result, $\alpha_{ij} \le e_{ij} \le \beta_{ij}$. When e_{ij} is a positive indicator, define the order parameter orderliness, that is

$$w_{ij} = (e_{ij} - \beta_{ij})/(\alpha_{ij} - \beta_{ij}) \quad (2)$$

When e_{ij} is a inverse indicator, define the order parameter orderliness, that is

$$w_{ij} = (\alpha_{ij} - e_{ij})/(\alpha_{ij} - \beta_{ij}) \quad (3)$$

In equations (2) and (3), when w_{ij} gets closer to 1, the greater the contribution of the order parameter e_{ij} to the subsystem. Therefore, the total contribution value w_i of each order parameter in each subsystem can be calculated using the following formula, that is

$$w_i = \sum_{j=1}^{m} \lambda_{ij} w_{ij}, \lambda_{ij} \ge 0, \sum_{j=1}^{m} \lambda_{ij} = 1 \quad (4)$$

In equation (4), λ_{ij} represents the weight of indicator *j* in subsystem *i*. Since the collaborative system constructed includes the subsystems of industry chain , innovation chain and talent chain , the capacity coupling system model is used to define the system coupling correlation degree C. The calculation formula is

$$C = \sqrt[3]{w_1 w_2 w_3} / [(w_1 + w_2 + w_3)/3] \quad (5)$$

On the basis of equation (5), a dynamic coupling coordination model is introduced, and T is defined as the comprehensive index of collaborative development among t the subsystems of industry chain , innovation chain and talent chain. Therefore, we set T=πw1+ϱw2+μw3, and π+ϱ+μ=1. The final expression for the synergy degree of "three chains" covering the subsystems of industry chain, innovation chain and talent chain, that is

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$$TID = \sqrt{C \times T} \quad (6)$$

In equation (6), the larger the TID value, the higher the fusion degree of "three chains". Because of subsystems of industry chain, innovation chain and talent chain are equally important, thus setting π=ρ=μ=1/3. Referring to the idea of constructing indicators based on Qi (2024), and considering the availability of datas at the city level, this study establishes a comprehensive evaluation index system for integration of "three chains". Which including three subsystems, six primary indicators, and twelve secondary indicators (Table 2). After weighting with entropy method, the degree of integration index for "three chains" in cities can be calculated.

Table 2. Comprehensive evaluation index system of Integration of "three chains".

Overall system	Subsystem	Primary Indicators	Secondary Indicators	Attribute
Integration Degree of "Three Chains"	Industry Chain	Industrial Foundation	Advanced industrial structure(Value added of tertiary industry/Value added of secondary industry)	+
			Rational structure of production(Theil Index)	−
		Industrial Benefits	Total output value of industrial enterprises above designated size	+
			Total profit of industrial enterprises above designated size	+
	Innovation Chain	Innovation Investment	Technology expenditure/general budget expenditure of local finance	+
			Number of scientific research and technology service practitioners/number of practitioners	+
		Innovation Output	Number of authorized invention patents	+
			Sales revenue from new products of industrial enterprises above designated size	+
	Talent Chain	Talent Environment	Education expenditure/general budget expenditure of local finance	+
			Number of students enrolled in regular higher education institutions/permanent population	+
		Talent Efficiency	The sum of actual added value of the first, second, and third industries/number of employees	+
			Number of newly established enterprises/permanent population in that year	+

The specific calculation formula for the Theil Index in Table 1 is shown in equation (7). Among them, Y_n/Y represents the proportion of the added value of the n industry to GDP, L_n/L represents the proportion of the number of employees in the n industry to the total number of employees, the Theil index is a reverse indicator (Li et al., 2026)

$$TI = \sum_{n=1}^{3} \left(\frac{Y_n}{Y}\right) Ln\left(\frac{Y_n}{Y} / \frac{L_n}{L}\right) \quad (7)$$

3.2.2. Dependent Variable

The single factor carbon index truly reflects the efficiency of carbon factor utilization, which can intuitively demonstrate the relationship between carbon emissions and economic output. It is currently the mainstream carbon productivity evaluation index (Hu & Wu, 2024). This study expresses urban carbon productivity as the ratio of actual GDP to carbon emissions(Meng & Zhao, 2023), where carbon emissions are measured using the calculation method in IPCC (2006).

3.2.3. Control Variables

This study selected the following five control variables: (1) Population density (*PD*), expressed as the logarithm of the ratio of urban permanent population to urban administrative area. (2) Urbanization rate (*UR*), which is the ratio of the number of permanent residents to permanent residents in urban areas . (3) The Financial Self Sufficiency Rate (*FSR*), which is expressed as the ratio of the general budget revenue to the general budget expenditure within the general fiscal budget of local governments. (4) The level of financial development (*FI*), which is measured by the ratio of the year-end loan balance in financial institutions to GDP. (5) Environmental Regulation (*ER*), which is obtained by collecting the indicators of industrial “three wastes” (including industrial wastewater emissions, industrial sulfur dioxide emissions, industrial smoke and dusk emissions), then calculating the comprehensive index of environmental regulation by using the entropy method.

3.2.4. Mechanism Variables

Referring to the measurement method of related researchers (Wang et al., 2023; Lou et al., 2023), the level of urban industrial agglomeration is measured by industrial added value location entropy and employment density. Drawing on the train of thought proposed by Guo et al. (2023), we can represent green technology innovation through the number of granted green invention patents. Referring to the ideas of related scholars(Yang & Pu, 2024), the logarithm of the number of urban digital invention patent authorizations is used as a measure of digital technology innovation. For the convenience of data processing, add 1 to the number of patents mentioned above and take the logarithm. Natural gas is a kind of green and environmentally friendly high-quality energy source, which has a relatively small impact on the natural environment. Therefore, drawing on the measurement approach of academic researcher(Wu et al., 2024), the energy structure is characterized by the proportion of natural gas consumption to total energy consumption, which is the proportion of clean energy consumption. The larger the ratio, the more reasonable the energy structure, which is a positive indicator. Coal is the dominant consumer energy in China’s economy and society, which has a negative impact on the development of green transformation. As the leading role in China’s national economy, industry is the main sector that generates carbon emissions. Therefore, referring to the method proposed by academic experts(Yao & Wang, 2023), the ratio of industrial electricity consumption to total social electricity consumption is used as a substitute variable for energy structure. The larger the proportion, the more unreasonable the energy structure, which is a negative indicator.3.1 Model setting.

3.3. Data Description

Due to the high number of missing values in data for various cities before 2003, and the fact that indicators such as industrial wastewater discharge are no longer updated after 2021, the sample observation period selected for this study is from 2003 to 2021. At the same time, this article does not include cities such as Bijie, Tongren, Longnan, and Zhongwei that were only established in 2004 or later, as well as cities with high missing values such as Lhasa, Turpan, and Hami. Therefore, the research sample includes 281 prefecture level and above cities in China. The original data mainly comes from the “China City Statistical Yearbook”, statistical yearbooks and bulletins of various provinces and cities. GDP is processed using the inflation index based on 2000 year, as well as index like the total output value and profits of industrial enterprises above a certain scale. All patent indicators are sourced from Chinese Research Data Service Platform(CNRDS), the missing data in the sample are filled in using linear interpolation. Descriptive statistics of variables are shown in Table 3.

Table 3. Descriptive statistics.

Classification	Designation	Sample Size	Mean	Variance	Min	Median	Max
Core Explanatory Variable	*TID*	5339	0.079	0.029	0.031	0.072	0.220
Dependent Variable	*CP*	5339	0.434	0.484	0.010	0.272	4.834
	PD	5339	2.489	0.416	0.697	2.526	3.947
	UR	5339	0.524	0.166	0.065	0.506	1.000
Control Variables	*FSR*	5339	0.473	0.224	0.026	0.440	1.541
	FI	5339	0.945	0.581	0.075	0.780	9.528
	ER	5339	0.931	0.068	0.332	0.948	0.999

Data source: Calculated and organized by the author.

4. Empirical Results

4.1. Benchmark Regression

Before further exploring the causal relationship between the integration of "three chains" and urban carbon productivity, there is a first test about multicollinearity in the explanatory variables. Due to the variance inflation factor test showing an average value of 1.95 and a maximum value of 2.9, both less than 10. Therefore no multicollinearity exists among the explanatory variables. The Hausman test results showed rejection of the null hypothesis, indicating that the fixed effects model is superior to the random effects model. Therefore, a bidirectional fixed effects model that controls for both entity and time was chosen. To enhance the comparison, only the core explanatory variable was added for mixed regression in column (1), fixed effects of entity and time were controlled for in column (2), control variables were added in mixed regression, which was performed in column (3), the bidirectional fixed effects regression results after adding control variables are shown in column (4).

The benchmark regression results in Table 5 show that the estimated coefficients of the core explanatory variable TID in all models are positive and have passed the significance test at the 1% level, thus indicating that there is always a positive correlation between the integration of "three chains" and urban carbon productivity. The test results are consistent with theoretical expectations, indicating that the integration of "three chains" can improve urban carbon productivity significantly, and H1 has been validated. This conclusion is a further expansion of the integration of "dual chains" to empower urban low-carbon transformation (Li et al., 2023). Because the integration of "three chains" focuses on energy conservation and emission reduction while achieving economic growth, helping the coordinated development of the two major goals of "carbon reduction" and "efficiency improvement", thereby improving urban carbon productivity, furthermore promoting sustainable economic and social development in cities.Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

Table 5. Benchmark regression.

	(1)	**(2)**	**(3)**	**(4)**
TID	11.739***	10.833***	11.663***	9.594***
	(0.329)	(1.230)	(0.440)	(1.094)
PD			-0.038**	0.796***
			(0.017)	(0.200)

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UR			-0.349***	-0.198
			(0.044)	(0.125)
FSR			0.243***	0.0453
			(0.037)	(0.066)
FI			0.058***	0.027*
			(0.015)	(0.015)
ER			-0.299**	0.328
			(0.118)	(0.229)
Constant Term	-0.495***	-0.385***	-0.102	-2.550***
	(0.023)	(0.074)	(0.120)	(0.587)
Entity Fixed	NO	YES	NO	YES
Time Fixed	NO	YES	NO	YES
Sample Size	5339	5339	5339	5339
R^2	0.486	0.569	0.501	0.591

Note: The robust standard error is within (), *, * *, * * * indicating significance at 10%, 5%, and 1% levels.

4.2. Robustness Test

To verify the robustness of the benchmark regression results, the following method is used for robustness testing based on the bidirectional fixed effects model. Firstly, data winsorizing. Considering that outliers may have an impact on the regression results, all continuous variables were double tailed at a 1% ratio, and the regression was fitted in column (1). Secondly, eliminate special samples. Considering the special nature of administrative levels that may affect the fitting effect, regression analysis is conducted in column (2) after excluding samples of municipalities directly under the central government, provincial capitals, and vice provincial cities. Thirdly, subsample regression. Considering that special events such as the SARS epidemic in 2003, the global financial crisis in 2008, and the full outbreak of the COVID-19 in 2020 may have an impact on the regression results, the subsample interval from 2009 to 2019 is intercepted and regression analysis is conducted in column (3) in order to ensure the continuity of the sample. Fourth, increase Control Variables. Further control the indicators of government intervention, industrial scale, and per capita road area, bringing them into column (4) for fitting regression. Fifth, explanatory variable lags behind by one period. Considering that cities with high carbon productivity may place more emphasis on cultivating the integration of “three chains”, in order to alleviate endogeneity bias caused by reverse causality, the lagged values of all explanatory variables are included in column (5) for regression analysis. Sixth, instrumental variable method. Using the lagged one period value of the integration degree of “three chains” as the instrumental variable, endogeneity testing was conducted using the panel instrumental variable method.

In Table 6, the test results from columns (1) to columns(4) show that the estimated coefficient of the core explanatory variable TID did not show significant changes, and still remains significantly positive at the 1% level after tail reduction after winsorization, removal of special samples, regression subsamples, and addition of control variables, verifying the robustness of the benchmark regression results. The test results of column (5) indicate that the parameter estimates of TID are significantly positive at the 1% level after lagging all explanatory variables by one period, and the results are still robust, ruling out endogeneity issues caused by reverse causality. The test results in column (6) show that the p-value of the K-P rk LM statistic is 0.0000, and the K-P rk Wald F statistic is greater than the critical value of 16.38 at the 10% level of the weak identification test, passing the “unidentifiable test” and “weak instrumental variable test”. As the parameter estimation values are significantly positive at the 1% level, it indicates that the positive impact of “three chain” integration on urban carbon productivity has passed endogeneity test.

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Table 6. Robustness test.

	(1) Winsorize	(2) Eliminate Special Samples	(3) Subsample	(4) Increase Control Variables	(5) Lagged Explanatory Variables	(6) Instrumental Variable Method
TID	9.070***	7.082***	7.690***	9.348***	9.817***	11.955***
	(0.927)	(0.948)	(1.210)	(1.097)	(1.108)	(1.227)
K-P rk LM Statistic						100.61 [0.0000]
K-P rk Wald F statistic						450.655 {16.38}
Control Variables	YES	YES	YES	YES	YES	YES
Entity Fixed	YES	YES	YES	YES	YES	YES
Time Fixed	YES	YES	YES	YES	YES	YES
Sample Size	5339	4674	3091	5339	5058	5058
R^2	0.640	0.619	0.436	0.596	0.585	0.565

Note: The p-value is within [], the critical value at the 10% level of Stock-Yogo weak recognition test is within {}.

4.3. Heterogeneity Analysis

Cities are the center of regional economic and social development, which are gathering places for various innovative elements and resources.. Therefore, it is necessary to discuss whether the integration of "three chains" has different effects on urban carbon productivity under various heterogeneous conditions. The specific method is as follows: Firstly, whether it is a low-carbon pilot city. In order to establish a resource-saving and environmentally friendly society, China issued three batches of low-carbon pilot cities in 2010, 2012, and 2017 respectively. Based on this, this paper will divide the sample into low-carbon city group and non low-carbon city group, then perform fitting regression separately. Secondly, whether it is a new energy demonstration city. In January 2014, in order to promote the revolution of energy production and consumption, and promote the construction of ecological civilization, the National Energy Administration issued the "Notice of the National Energy Administration on Publishing the List of New Energy Demonstration Cities (Industrial Parks) (First Batch)". Based on this, this study will divide the sample into a new energy demonstration city group and a non new energy demonstration city group, then conduct group regression. Thirdly, whether it is a resource based city. In 2013, the State Council issued the "National Sustainable Development Plan for Resource based Cities (2013-2020)", which is the first time designated resource based cities as the guarantee areas for maintaining energy and resource security. According to the requirements of the document, this study will divide the sample into resource based city group and non resource based city group, then conduct heterogeneity tests separately. Fourth, whether it is a national innovative city. Accelerating the construction of innovative cities is conducive to enhancing independent innovation capabilities and accelerating the transformation of economic development mode. According to the "National Innovation City Innovation Capability Evaluation Report 2023" released by the Institute of Science and Technology Information in China, the top 100 cities included in the national innovation city innovation capability index will be divided into the innovation city group[101 cities participated in the evaluation on the "National Innovation City Innovation Capability Evaluation Report 2023", Lhasa was not included in the research sample due to a large number of missing values.]. The remaining cities will be divided into the non innovation city group, then perform regression analysis separately. The heterogeneity test results are shown in Table 7.

Table 7. Heterogeneity analysis.

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	Low-carbon Pilot Cities		New Energy Demonstration Cities		Resource Based Cities		National Innovative Cities	
	YES	**NO**	**YES**	**NO**	**YES**	**NO**	**YES**	**NO**
TID	10.105*** (1.662)	8.543*** (1.160)	13.284*** (1.822)	8.005*** (1.190)	4.629*** (1.141)	11.774*** (1.273)	11.105*** (1.844)	2.894*** (0.630)
Control Variables	YES	YES	YES	YES	YES	YES	YES	YES
Entity Fixed	YES	YES	YES	YES	YES	YES	YES	YES
Time Fixed	YES	YES	YES	YES	YES	YES	YES	YES
样本量	2318	3021	1178	4161	2128	3211	1900	3439
R^2	0.590	0.607	0.617	0.596	0.495	0.635	0.672	0.551

Note: The robust standard error is within (), *, * *, * * * indicating significance at 10%, 5%, and 1% levels.

4.3.1. Heterogeneity Analysis of Low-Carbon Pilot Cities

In both the low-carbon pilot city and non low-carbon pilot city groups, the parameter estimation values of TID are positive and have passed the significance test at 1% level. This conclusion indicates that the integration of “three chains” can have a positive impact on urban carbon productivity regardless of it is a low-carbon pilot city or not. In terms of the estimated coefficient size of TID, low-carbon pilot cities are significantly larger than non low-carbon pilot cities, thus indicating that the integration of “three chains” is more conducive to improving the carbon productivity in low-carbon pilot cities. On the one hand, the main reason is that the low-carbon city pilot policy has a positive promoting effect on the high-quality development of urban economy (Fan & Guo, 2023). Green and low-carbon development, as key elements of high-quality development, can help reduce carbon dioxide emissions and improve urban carbon sequestration neutrality capabilities, which is crucial for promoting the improvement of urban carbon productivity. On the other hand, the government has set stricter low-carbon development goals, and application of green low-carbon technologies is more widespread in low-carbon pilot cities. Due to the demonstration effect is stronger, the industrial structure is better. Therefore, the combined effect of these factors gives low-carbon pilot cities a significant advantage in improving carbon productivity through the integration of “three chains”.

4.3.2. Heterogeneity Analysis of New Energy Demonstration Cities

In both the new energy demonstration city and non new energy demonstration city groups, the estimated coefficient of TID is significantly positive at 1% level, which indicates that there is always a positive correlation between the integration of “three chains” and urban carbon productivity regardless of it is a new energy demonstration city or not. The parameter estimation values of TID in the sample of new energy demonstration cities are significantly higher than those in non new energy demonstration cities, thus indicating that the integration of “three chains” has a better effect on improving urban carbon productivity in new energy demonstration cities. There may be two reasons for this. On the one hand, new energy demonstration cities have raised public awareness of low-carbon through extensive publicity and educational activities. Enterprises may adopt low-carbon production and operation methods actively, and pay more attention to energy conservation and emission reduction, thus creating a excellent social environment to improve urban carbon productivity. On the other hand, new energy demonstration cities have vigorously promoted renewable resources such as solar, wind, and hydro energy, which promotes the diversification of energy use, and reduces dependence on traditional fossil fuels, thereby helps to reduce carbon emissions and improve carbon productivity.

4.3.3. Heterogeneity Analysis of Resource Endowment

In both resource based and non resource based city groups, the estimated coefficient of TID is significantly positive at 1% level, which indicates that the integration of “three chains” has a positive

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impact on urban carbon productivity regardless of it is a resource based city or not. The parameter estimation values of TID in resource based cities are lower than those in non resource based cities, thus indicating that the integration of “three chains” has a more significant effect on improving carbon productivity in non resource based cities. The main reason is that the dominant industries in resource based cities are mostly based on the extraction and processing of natural resources such as coal, oil, and non-ferrous metals in the region. For a long time, this extensive economic development model has increased carbon dioxide emissions. At the same time, factors such as incomplete development of the industry chain, insufficient technological innovation, and lack of talent have led to a low degree of integration of “three chains” in resource based cities. For non resource based cities, economic development does not rely on resource endowments overly, industries are more diversified, and innovation and talent resources are more abundant. Therefore, the integration of “three chains” has a more significant effect on improving carbon productivity in non resource based cities than in resource based cities.

4.3.4. Heterogeneity Analysis of National Innovative Cities

In the groups of innovative and non innovative cities, the parameter estimate of the core explanatory variable TID is significantly positive at 1% level, which indicates that the integration of “three chains” has a positive impact on urban carbon productivity regardless of it is an innovative city or not. The estimated coefficient of TID in the sample of innovative cities is significantly higher than that in non innovative cities, thus indicating that accelerating the construction of innovative cities is conducive to promoting the positive impact of the integration of “three chains” on urban carbon productivity. One reason for this phenomenon is that the pilot policy for innovative cities is not only conducive to promoting the deep integration of the industry chain, innovation chain, and talent chain, but also an important measure to promote sustainable urban development. The other reason is that, innovative pilot policies have effectively promoted the enhancement of urban independent innovation capabilities, they have forced green technology innovation by attracting innovative elements to gather, thereby promoting urban green development (Liu et al., 2023). In addition, the construction of innovative cities may reduce carbon emissions through resource allocation and structural optimization effects, thereby helping to further improve the level of urban carbon productivity.

4.4. Mechanism Verification

To investigate the transmission mechanism of the integration of “three chains” on urban carbon productivity, a regression model of equation (8) is constructed. Among the econometric model, MEDmt represents mechanism variables, including industry agglomeration, technology innovation, and energy structure. The mechanism test results are shown in Table 8.

$$MED_{mt} = \beta_0 + \beta_1 TID_{mt} + \beta \sum X_{mt} + u_m + v_t + \varepsilon_{mt} \quad (8)$$

Table 8. Mechanism verification.

	Industry Agglomeration		Technology Innovation		Energy Structure	
	Location Entropy	Employment Density	Green-tech Innovation	Digital-tech Innovation	Proportion of Clean Energy	Proportion of Industrial Electricity
TID	0.742** (0.298)	0.340** (0.168)	39.506*** (2.308)	41.549*** (2.971)	1.598*** (0.459)	-1.143*** (0.353)
Control Variables	YES	YES	YES	YES	YES	YES
Entity Fixed	YES	YES	YES	YES	YES	YES
Time Fixed	YES	YES	YES	YES	YES	YES

Sample Size	5339	5339	5339	5339	5339	5339
R^2	0.261	0.212	0.789	0.838	0.075	0.067

Note: The robust standard error is within (), *, * *, * * * indicating significance at 10%, 5%, and 1% levels.

4.4.1. Transmission Mechanism of Industry Agglomeration

The test of industrial agglomeration mechanism shows that the estimated parameter value of the core explanatory variable TID is significantly positive at 5% level, which indicates that the integration of "three chains" has a positive impact on industrial agglomeration. The reason is that the integration of "three chains" has promoted the concentration of related enterprises in geographical space, and the enterprises within the cluster are interrelated and interdependent. With the help of knowledge sharing and technology spillover, the coordinated development of the upstream and downstream of the industry chain and the gathering of talents have produced industrial agglomeration effects. That is to say, the integration of "three chains" has promoted the formation and development of industrial agglomeration jointly through the extension of industry chain, the driving force of innovation chain, and the support of talent chain. Industrial agglomeration fully leverages the benign competition among enterprises, thus making it possible for them to form alliances and cooperate, ultimately stimulating the use of high-tech to reduce carbon emissions and improve carbon productivity (Meng & Zhao, 2023). Therefore, the integration of "three chains" can enhance urban carbon productivity through promoting industrial agglomeration. H2 has been tested.

4.4.2. Transmission Mechanism of Technology Innovation

The test of technological innovation mechanism shows that the parameter estimation values of TID are significantly positive and have passed the significance test at 1% level. This indicates that the integration of "three chains" not only promotes the progress of green technology, but also enhances digital technology innovation. The main reason is that the integration of "three chains" has promoted deep cooperation between the government, universities, research institutions and enterprises. The cooperation model may integrate the advantageous resources of all parties, and form an innovative synergy, thus promoting the transformation of green and digital technologies, and providing technical support for improving carbon productivity. During the process in the integration of "three chains", the market's demand for "green" and "digital" products is gradually increasing, which helps to promote the continuous progress of green technology and digital technology, thus leading to the continuous improvement in level of urban green technology innovation and digital technology innovation. Against the backdrop of the rapid development of digital economy and the achievement of "dual carbon" goal, as important components of technological innovation, green technology innovation and digital technology innovation can achieve "emission reduction" and "efficiency enhancement" (Hu & Shen, 2023). Therefore, technological innovation has a long-term promoting effect on carbon productivity (Pei & Chen, 2023). In summary, the integration of "three chains" has a positive impact on urban carbon productivity by promoting technological innovation, with green technology innovation and digital technology innovation playing important transmission roles, which verifies H3.

4.4.3. Transmission Mechanism of Energy Structure

The mechanism test of energy structure shows that the estimated coefficients of TID have passed 1% significance level. The regression results in column (5) shows that the estimated parameters of TID are positive, which indicates that the integration of "three chains" can effectively increase the ratio of clean energy, thus optimizing the energy structure. The regression results in column (6) shows that the estimated parameter values of TID are negative, which indicates that the integration of "three chains" has a negative impact on the proportion of industrial electricity consumption. Due to industrialization process leading to significant energy consumption in China, the combustion of fossil fuels such as coal is the main cause of ecological degradation (Ma & Liu, 2024). Therefore, the

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integration of “three chains” has significantly reduced the proportion of coal consumption and further optimized the energy structure. The main reason for the above phenomenon is that the integration of “three chains” may promote the rise of the new energy industry and the transformation and upgrading of traditional industries. The most direct manifestation is the increase in the use of clean energy and the reduction of fossil energy consumption, especially in the link of energy production, processing, conversion, and consumption. The integration of “three chains” has optimized the energy structure from the supply side, promoted the energy consumption revolution, and contributed to the sustainable development of the economy and society. Due to the positive driving effect of energy structure transformation on carbon productivity (Sun & Du, 2020), Therefore, the integration of “three chains” can improve urban carbon productivity by optimizing the energy structure. H4 has been verified.

5. Conclusions and Policy Implications

5.1. Research Conclusion

This study has analyzed the internal logic of “three chains” integration based on the triple helix theory, incorporated the integration of “three chains” and urban carbon productivity into the same research framework. Panel data from 281 prefecture level and above cities in China from 2003 to 2021 were used to measure the degree of “three chains” integration through a composite system synergy model, thus examining the influence of “three chains” integration on urban carbon productivity. The research conclusions are as follows:

First, the benchmark regression test results indicate that the integration of “three chains” has a positive impact on improving urban carbon productivity. After winsorization of data, removal of abnormal samples, regression sub samples, addition of control variables, and consideration of endogeneity issues, the positive impact of “three chains” integration on urban carbon productivity remains robust.

Second, the heterogeneity test results indicate that there are significant heterogeneity characteristics in the impact of “three chains” integration on urban carbon productivity. The integration of “three chains” can better promote the improvement of urban carbon productivity in low-carbon pilot cities, new energy demonstration cities, non resource cities, and national innovation cities.

Third, the mechanism test results indicate that the integration of “three chains” indirectly improves urban carbon productivity through promoting industrial agglomeration, driving technological innovation, and optimizing energy structure.

5.2. Policy Implications

5.2.1. Promote the Deep Integration of “Industry-Innovation-Talent Chains”

Pay attention to the positive role of the integration of “three chains” on promoting urban carbon productivity, and promote the deep integration of “industry-innovation-talent chains”. Firstly, it is necessary to establish a systematic concept, and focus on the major strategic needs of the country and the direction of industrial development, promote the formation of a collaborative innovation and integrated development industry chain with the goal of breaking through key core technologies and enhancing industrial basic capabilities and industrial benefits. Secondly, we need to strengthen the cultivation of innovation chains, increase innovation investment through policy guidance and market mechanisms, stimulate the vitality of innovation entities such as enterprises, universities, and research institutes, create an open and cooperative atmosphere, thus promoting the transformation and industrial application of innovative achievements. Finally, we should improve the construction of the talent chain, and strengthen talent cultivation and introduction centered around demands of the industry chain and innovation chain. It is suggested to establish a sound talent incentive

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mechanism to stimulate the innovative and creative consciousness of talents, which would provide strong support for the deep integration of the industry chain, innovation chain, and talent chain.

5.2.2. Recognize Regional Disparities and Balance Development of Urban Low-Carbon Transformation

This research has shown that the integration of "three chains" is more conducive to improving urban carbon productivity in low-carbon pilot cities, new energy demonstration cities, non resource based cities, and national innovative cities. On the one hand, it is necessary to actively promote the successful experience of pilot cities in promoting the process of urban green development. We should promote the improvement of urban carbon productivity level and achieve regional green and balanced development jointly through a point to area approach. On the other hand, we need to pay attention to classification guidance, and promote the integration of "three chains" in an orderly manner according to local conditions. For example, for cities lacking policy support, the government should focus on overall planning, establish a coordinated development mechanism for industrial subsidies, innovation incentives, and talent introduction, thus leading to create a suitable development environment for promoting the integration of "three chains" deeply. For non resource based cities, it is necessary to cultivate the concept of green development under the existing resource endowment conditions, adhere to the principle that green mountains and clear waters are as valuable as gold and silver. Learning to transform the economic development mode and promote the low-carbon transformation of cities.

5.2.3. Promote Industry Agglomeration and Technology Innovation, Optimize Energy Structure

We should stimulate the important conduction effects of industry agglomeration, technology innovation and energy structure in the process of "three chains" integration on improving urban carbon productivity. Firstly, it is necessary to strengthen top-level design, establish the concept of circular economy, and improve the mechanism of industrial agglomeration development through integrating enterprise resources. It is suggested to improve the industry chain, promote the extension of the industry chain, form a coordinated development trend between upstream and downstream, and promote high-quality development of industrial agglomeration according to the dominant industries. Secondly, it is necessary to establish a technology innovation platform with enterprises as the main body, market as the orientation, and the participation of the government, universities and research institutions, thus promoting the "greening" and "digitization" of technological innovation jointly. Finally, we may establish a reasonable energy consumption model with the goal of controlling high carbon energy consumption and promoting diversified energy development, and further deepen energy system reform, thus establishing a fair, open, and competitive energy system.

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