Coupling Coordination Analysis between Circular Economy and Green Supply Chain: A Case Study of China’s Eastern Economic Belt

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Abstract: Against the backdrop of prominent environmental issues, sustainable economic development is faced with higher demands, urgently requiring the promotion of green transformation. This study constructs a circular economy and green supply chain system with 17 indicators. It measures the coupling coordination degree of 10 eastern provinces and municipalities from 2010 to 2022 by the entropy-weight method, TOPSIS, and the coupling coordination degree model. The results show that the coupling coordination level is generally in the transitional coordination stage and shows a growth trend. There are differences in development among the provinces. Provinces with significant resources and industrial advantages, such as Shandong and Hebei, have a higher level of coordination. Certain provinces, such as Hainan, started late but have gradually improved under policy and market-driven conditions. Functionally adjusted regions have insufficient incentives for transformation, such as Beijing. This study provides a data-driven reference for promoting the optimization of China's green transformation.

Keywords: Eastern Economic Belt; Circular Economy; Green Supply Chain; Coupling Coordination Degree Model

1. Introduction

Global climate change and over-consumption of resources are seriously affecting the process of sustainable development of human, placing higher demands on economic activities and industrial chains. Rising temperatures will impair labor productivity, disrupt supply chains, and are likely to cost the global economy as much as $24.70 trillion [1]. Meanwhile, global resource consumption shows an exponential increase. It will increase eight times in the late 21st century, with huge pressure on the sustainable development of the economy [2]. Therefore, it is urgent to promote economic development and structural upgrading of industries through green transformation.

Circular economy (CE) is widely recognized as a sustainable economic pattern. CE is the design and management of processes and outputs, such as planning, resource allocation, procurement, production, and reprocessing, to enhance ecosystem functions and human well-being [3]. Supply chain is one of the core industrial chains to practice the CE pattern. Among them, the traditional supply chain urgently needs to be transformed into the green supply chain (GSC) [4]. GSC focuses on the procurement of raw materials, production, transport, sales, recycling, and other links to carry out green innovation and transformation. It promotes the implementation of closed-loop resource utilization and the win-win situation of economic and ecological benefits.

Coupling refers to the phenomenon of two or more systems influencing each other through various interactions, which is a concept originating from physics [5]. It emphasizes the positive interaction among the components of the system, promoting the positive cyclic development among the systems while maintaining the harmony and health of internal elements [6]. Recently, coupling theory has been widely used by scholars in many fields. The research objects cover diverse topics such as ecological investment and CE, environment, energy and economic growth, economy and ecology, which provide vital references for China's sustainable development path. As for the supply chain, scholars have already integrated the green concept into supply chain management. For example, Genovese et al. verified that integrating the principles of CE into the sustainable supply chain management can significantly reduce carbon emissions by using a hybrid life-cycle assessment method [7]. Existing studies still have shortcomings. On the one hand, the systematic coupling mechanism between GSC and CE has not yet formed a complete research system. On the other hand, the completeness of the synergistic effect between the two systems, as revealed by indicators, needs to be further explored.

Under the backdrop of carbon peaking and carbon neutrality goals, this study selects the panel data of the ten strong economic provinces in eastern China from 2010 to 2022. And it takes featured indicators such as logistics carbon emissions, share of green tax revenue, and the number of waste resources utilization enterprises into the system framework. The entropy weight method (EWM), the technique for order preference by similarity to ideal solution (TOPSIS), and the coupling coordination degree model (CCDM) are used to conduct empirical research to reveal the dynamic synergistic development law of GSC and CE.

2. Methodologies

2.1 Study Area

The Eastern Economic Belt of China consists of seven provinces, namely Hebei, Shandong, Jiangsu, Zhejiang, Fujian, Guangdong, and Hainan, and three municipalities, namely Beijing, Tianjin, and Shanghai [8]. In 2023, the area created 51.7% of China's GDP on only 9.8% of the country's land area [9]. The region has achieved remarkable results in green and low-carbon practices. For example, Shandong has promoted about 100 parks and 90 GSC management enterprises to complete the recycling transformation by 2023 [10]. Provinces and municipalities in the area remain heterogeneous in their green transformation. For example, Shanghai urgently needs to explore efficient utilization patterns due to resource constraints, while Hainan needs to find a balance between decarbonization of tourism and economic growth. Disparities have led to insufficient impetus for green transformation. The synergistic effect of CE and GSC has not been fully utilized, affecting the overall effectiveness of the transformation. Therefore, there is a need to study the synergistic mechanism of the two in the area and then provide a reference for the green upgrading of industries nationwide, as shown in Figure 1.

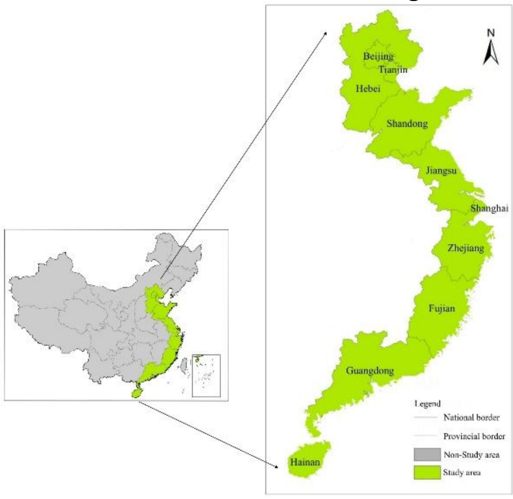


Figure 1. Schematic Representation of the Study Area

2.2 Data Sources and Data Pre-Processing

Based on data accessibility and integrity, this study takes provinces as the evaluation units and selects the period from 2010 to 2022 as the study period. The data are obtained from statistical yearbooks, including China Statistical Yearbook, China Electric Power Yearbook, China Energy Statistical Yearbook, and China Urban Construction Statistical Yearbook. For the few missing data, the linear interpolation method is adopted to fill in.

To eliminate the influence of the differences in the scale and units of the indicators on the assessment results and improve the comparability of the data, min-max normalization is applied to the indicators.

For positive indicators:

$$Y_{ij} = \frac{X_{ij} - X_{\min j}}{X_{\max j} - X_{\min j}} \tag{1}$$

For negative indicators:

$$Y_{ij} = \frac{X_{\max j} - X_{ij}}{X_{\max j} - X_{\min j}} \tag{2}$$

Where, Y_{ij} is the standardized value. X_{ij} is the original value of the j indicator for the i evaluation unit. $X_{\max j}$ and $X_{\min j}$ are the maximum and minimum values of the j indicator, respectively. To prevent interference by the zero value on the subsequent calculations, a small corrected value $\partial = 0.00001$ is added to Y_{ij} so that $Y_{ij} \in (0,1]$.

2.3 Methods

2.3.1 Construction of the Indicator system

The theoretical framework of CE is closely related to the practical demands of the "3R" principle which is Reduce, Reuse, and Recycle [11]. It aims to promote the transformation of the economy from the traditional linear pattern of make-use-discard to the closed-loop pattern of make-use-reuse [12], constituting the core logic of the development of CE. Based on this, the construction of the comprehensive evaluation indicators of CE should follow three core guidelines: (1) Input Reduction is to lower resource consumption in production process; (2) Recycle and Reuse is to the strengthen the flow and use of resources; (3) Pollution Minimization is to reduce the negative impact of pollutant emissions on the environment. According to the product life cycle theory, the core of GSC lies in the effective use of resources and the reduction of waste in each link [13], including the whole process from product design, procurement, production, transport, storage, sale, use, to end-of-life treatment. Focusing on the impact of the core links, the construction of the comprehensive evaluation indicators of GSC should follow three core guidelines: (1) Green Production corresponds to manufacturing; (2) Green Logistics corresponds to transport and storage; (3) Green Consumption corresponds to usage and end-of-life treatment. As shown in Table 1, a total of 17 indicators are selected.

Table 1. Indicator System

Target layer	Criterion Layer	Indicator Layer	Unit	Attribute	**Indicator Definition**
CE	Input Reduction	Volume of water saved	10,000 m^3	+	Reduction in water use through conservation measures
		Land area used for industry per GDP	km^2/billion yuan	-	Land area used / GDP
	Recycle and Reuse	Ratio of industrial solid wastes utilized	%	+	Industrial solid wastes comprehensively utilized / (Industrial solid wastes generation + Stock of previous years' industrial solid wastes)
		Ratio of industrial water reuse	%	+	Industrial water reuse/Total industrial water use
		Number of waste resources utilization enterprises	units	+	Reflect scale and development level of waste resources industry
		Ratio of municipal domestic garbage harmless treatment	%	+	Amount of non-hazardous domestic garbage treated/Amount of domestic garbage generated
	Pollution Minimization	Average concentration of PM_{10} in air	mg/m^3	-	Sum of daily average PM_{10} concentrations/Number of monitoring days
		Industrial pollution control investment	billion yuan	+	Total investment in industrial pollution control
		Sulphur dioxide emission in waste gas	10,000 tons	-	Waste gas flow × Sulphur dioxide concentration
		Ammonia-nitrogen discharged in waste water	10,000 tons	-	Waste water flow × Ammonia-nitrogen concentration
GSC	Green Production	Energy consumption per GDP	tons of standard coal/million yuan	-	Total energy consumption / GDP
		Water consumption per GDP	m^3/10,000 yuan	-	Total water consumption / GDP
		Share of renewable energy installed capacity	%	+	(Hydropower + Wind + Solar) / total installed capacity

	Green Logistics	Logistics carbon emissions	10,000 tons CO_2	-	Standard coal coefficient × Carbon emission coefficient × Energy consumption
		Share of green freight turnover	%	+	(Rail + Waterway freight turnover) / total freight turnover
	Green Consumption	Share of green tax revenue	%	+	(Resource tax + Environment protection tax) / General public budget revenue
		Public transport vehicles per 10,000 people	units	+	Number of public transport vehicles/urban population

2.3.2 EWM

Based on the information entropy theory, EWM was proposed by Shannon and Weaver in 1947, which is the most commonly used objective weighting method [14]. It measures the degree of change of the indicator through the information entropy: the smaller entropy value means the higher dispersion, the more information provided, the more useful it is in the assessment, and the higher weight is given accordingly [14]. Compared with subjective weighting methods, the greatest advantage of EWM is that it avoids the interference of subjective preferences of decision makers, thereby ensuring the objectivity of evaluation systems [15]. This method is used in this study to determine the weight of each indicator. The total weights of both systems are set to 100%. Its formulas are as follows:

$$\begin{cases} Z_{ij} = \dfrac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}} & (i=1,...n;\ j=1,...m) \\ E_j = \dfrac{\sum_{i=1}^{n} Z_{ij} \ln Z_{ij}}{-\ln n} & (E_j \geq 0) \\ W_j = \dfrac{1-E_j}{\sum_{j=1}^{m}(1-E_j)} \end{cases} \quad (3)$$

Where, Z_{ij} is the proportion of the indicator value. E_j is the information entropy. W_j is the weight of the indicator.

TOPSIS was proposed by Hwang and Yoon in 1981 and has been widely applied as a classic multi-attribute decision-making method in the past few decades [16]. It determines the relative merits of the alternatives by calculating the distance of each alternative from the positive and negative ideal solutions [16]. Based on the weights of indicators determined by EWM, this study subsequently analyses the decision normalization matrix using TOPSIS to determine the comprehensive evaluation values of CE and GSC, respectively, using the following formulas:

$$\begin{cases} A_{ij} = W_j \cdot Y_{ij} \\ A_j^+ = \{\max A_{ij}\} \\ A_j^- = \{\min A_{ij}\} \\ d_i^+ = \sqrt{\sum_{j=1}^{m} (A_{ij} - A_j^+)^2} \\ d_i^- = \sqrt{\sum_{j=1}^{m} (A_{ij} - A_j^-)^2} \\ S_i = \dfrac{d_i^-}{d_i^- + d_i^+} \end{cases} \quad (4)$$

Where, A_{ij} is the weighted normalized matrix. A_j^+ and A_j^- are positive and negative ideal solutions, respectively. d_i^+ and d_i^- are distances of the evaluation unit to A_j^+ and A_j^-, respectively. S_i is the degree of closeness to the ideal solution, which means the composite evaluation value.

2.3.4 CCDM

CCDM describes the interaction between two or more subsystems. Among them, the degree of coupling reflects the strength of the system interaction, while the degree of coordination reflects the level of synergistic development. This model has the ability to perform comprehensive system evaluation, is intuitive and easy to interpret, and has been widely applied [17]. Its formulas are as follows:

$$\begin{cases} T = a_1 \cdot U_1 + a_2 \cdot U_2 \\ C = 2 \cdot \sqrt{\dfrac{U_1 \cdot U_2}{(U_1 + U_2)^2}} \\ D = \sqrt{C \cdot T} \end{cases} \quad (5)$$

Where, T is the comprehensive coordination index. U_1 and U_2 are CE and GSC composite scores, respectively. a_1 and a_2 are system coefficients, both set to 0.5 due to equal importance. C is the coupling degree. The larger the value is, the higher the degree of coupling. D is the coupling coordination degree. The larger the value is, the higher the degree of coordination. Based on previous studies [18], the classification standards for coupling degree and coupling coordination degree are presented in Tables 2-3.

Table 2. The Classification Criteria of Coupling Degree

Coupling degree C	Stage
$0 < C \le 0.3$	Low coupling period
$0.3 < C \le 0.5$	Antagonistic period
$0.5 < C \le 0.8$	Break-in period
$0.8 < C \le 1.0$	High coupling period

Table 3. The Classification Criteria of Coordination Degree

Coordination Type	Coordination Degree D	Coordination Level
Dysfunctional Decline	(0.0,0.1)	Extreme disorder
	[0.1,0.2)	Severe disorder
	[0.2,0.3)	Moderate disorder
	[0.3,0.4)	Mild disorder
Transitional Coordination	[0.4,0.5)	On the verge of disorder
	[0.5,0.6)	Marginal coordination
Coordinated Elevation	[0.6,0.7)	Primary coordination
	[0.7,0.8)	Intermediate coordination
	[0.8,0.9)	Good coordination
	[0.9,1.0]	Optimal coordination

3. Research Results

3.1 Analysis of Development

Before calculating the degree of coordination of CE and GSC using CCDM, it is necessary to clarify the performance of the indicators under the geographical and time dimensions. This study analyses the raw data for representative indicators from both CE and GSC systems.

3.1.1 CE indicators

As shown in Figure 2, volume of water saved is significantly different in the 10 provinces and municipalities, showing fluctuating changes overall. Among them, coastal provinces such as Guangdong, Jiangsu, Shandong, and Zhejiang save much more water than other regions, indicating that the effectiveness of conservation is more prominent. The low values in regions such as Hainan and Tianjin are related to their small size and low water use base. Guangdong's figures have increased significantly since 2015, attributed to effective measures implemented to build a water-saving society.

As shown in Figure 3, number of waste resources utilization enterprises shows an overall growth trend, but the differences between provinces are more obvious. Among them, the figures of industrial provinces such as Jiangsu, Shandong, and Guangdong are greater than 150 on average. These provinces have formed industrial clusters of resource recycling based on their strong manufacturing base. On the other hand, Hebei has achieved leapfrog growth under the upgrading of traditional industries, with its figures growing at a rate of 5.9 times, ranking first. The figures of Hainan have been at a low level for a long time, and the resources utilization market is still in its infancy.

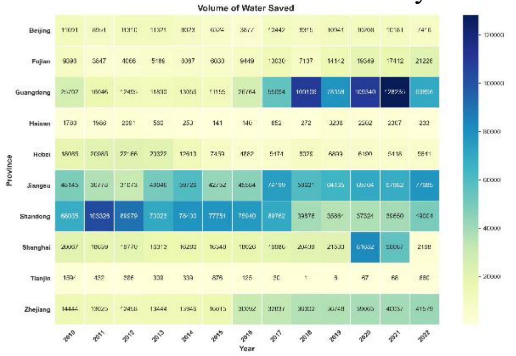


Figure 2. Volume of Water Saved by Province and Year

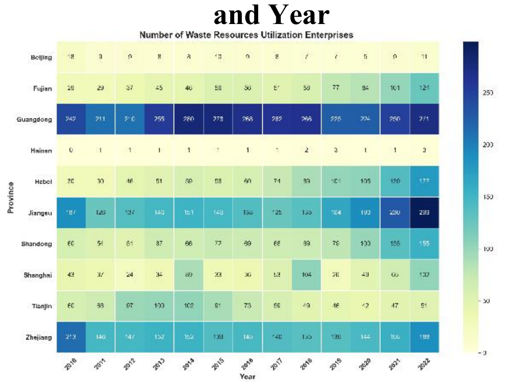


Figure 3. Number of Waste Resources Utilization Enterprises by Province and Year

3.1.2 GSC indicators

As shown in Figure 4, green tax revenue share generally shows an elevated trend, and the rapid growth of general public budget revenue may have pulled down the value in some years. Among them, the figures of Hebei and Shandong have been significantly higher than those of other provinces for a long time, with an average value of more than 2%. It is mainly because the industrial structures of the two provinces are dominated by heavy chemical industries, with outstanding demand for resources development and environmental governance. The figures for

Beijing and Tianjin increased in 2018. It is closely related to the tax for fees reform implemented by the Environmental Protection Tax Law of the People's Republic of China that year.

Figure 4. Share of Green Tax Revenue by Province and Year

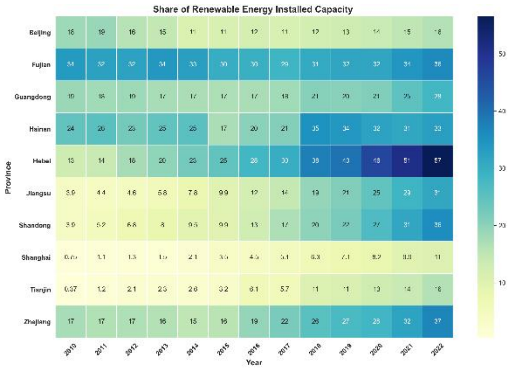


Figure 5. Share of Renewable Energy Installed Capacity by Province and Year

As shown in Figure 5, share of renewable energy capacity generally shows an upward trend, but the growth rate varies significantly. Among them, the growth rate of Hebei shows an explosive growth, jumping from 13.07% in 2010 to 56.55% in 2022. It reflects the rapid development of the province in the field of renewable energy. Beijing's slower growth rate is mainly due to its functional position focusing on the political and cultural center as well as the tight land resources which limit the layout of wind power and photovoltaic projects.

3.2 Analysis of Indicators Evaluation System

As shown in Table 4, the weight results of the indicators are calculated by EWM. In the CE system, there is an average share of Input Reduction (35.047%), Recycle and Reuse (31.521%), and Pollution Minimization (33.432%). It shows that this is in line with the current situation of CE, where source-process-end is synergistically promoted. The indicator of volume of water saved accounts for 92.250% of Input Reduction. The indicator of number of waste resources utilization enterprises accounts for 68.380% of Recycle and Reuse. The indicator of industrial pollution control investment accounts for 74.620% of Pollution Minimization. However, volume of water saved has a larger share. It reflects the real pressure of water resource constraints in the process of industrialization, and resource conservation remains one of the top priorities of synergistic development in various regions.

Meanwhile, in the GSC system, the share of Green Production (25.510%), Green Logistics (15.927%), and Green Consumption (58.563%) varies greatly. It reflects the fact that China's green transformation is at a stage where market demand is the main driver, and production and logistics are gradually following. The indicator of share of renewable energy installed capacity accounts for 70.298% of Green Production. The indicator of share of green freight turnover accounts for 70.315% of Green Logistics. The indicator of share of green tax revenue accounts for 74.001% of Green Consumption. However, share of green tax revenue has a larger share. It reflects the fact that the use of tax tools to promote green consumption is still a key measure for localities to implement the concept of green development and help the transformation of supply chains.

Table 4. Results of the Weighting of Indicators

Target layer	Criterion Layer	Indicator Layer	Information Entropy	Information Utility	Weight
CE	Input Reduction	Volume of water saved	0.886	0.114	32.332
		Land area used for industry per GDP	0.99	0.01	2.715
	Recycle and Reuse	Ratio of industrial solid wastes utilized	0.981	0.019	5.429
		Ratio of industrial water reuse	0.991	0.009	2.674
		Number of waste resources utilization enterprises	0.924	0.076	21.553
		Ratio of municipal domestic garbage harmless treatment	0.993	0.007	1.864
	Pollution Minimization	Average concentration of PM10 in air	0.995	0.005	1.279
		Industrial pollution control investment	0.912	0.088	24.948
		Sulphur dioxide emission in waste gas	0.987	0.013	3.561

		Ammonia-nitrogen discharged in waste water	0.987	0.013	3.644
GSC	Green Production	Energy consumption per GDP	0.99	0.01	4.372
		Water consumption per GDP	0.992	0.008	3.205
		Share of renewable energy installed capacity	0.957	0.043	17.933
	Green Logistics	Logistics carbon emissions	0.989	0.011	4.728
		Share of green freight turnover	0.973	0.027	11.199
	Green Consumption	Share of green tax revenue	0.896	0.104	43.338
		Public transport vehicles per 10,000 people	0.963	0.037	15.226

Table 5. Results of Coupling and Coordinating Calculations in 10 Provinces and Municipalities

Year		Beijing	Tianjin	Hebei	Shanghai	Jiangsu	Zhejiang	Fujian	Shandong	Guangdong	Hainan
2010	C	0.940	0.995	0.778	0.999	0.969	0.992	0.910	0.999	0.933	0.868
	D	0.380	0.426	0.548	0.428	0.550	0.526	0.455	0.646	0.515	0.343
2011	C	0.878	0.992	0.834	0.997	0.986	0.999	0.885	0.982	0.972	0.743
	D	0.393	0.434	0.571	0.423	0.522	0.500	0.433	0.679	0.503	0.349
2012	C	0.910	0.995	0.820	0.998	0.990	0.998	0.946	0.999	0.975	0.801
	D	0.411	0.456	0.595	0.424	0.530	0.501	0.461	0.742	0.510	0.387
2013	C	0.919	0.995	0.882	0.995	0.959	0.987	0.979	0.999	0.948	0.808
	D	0.420	0.459	0.638	0.416	0.569	0.526	0.482	0.723	0.514	0.374
2014	C	0.911	0.998	0.9440	0.999	0.952	0.983	0.982	0.999	0.949	0.772
	D	0.416	0.462	0.675	0.447	0.572	0.536	0.491	0.774	0.533	0.360
2015	C	0.892	0.999	0.947	0.999	0.957	0.988	0.987	0.999	0.949	0.825
	D	0.403	0.449	0.567	0.430	0.554	0.526	0.492	0.727	0.529	0.358
2016	C	0.901	0.989	0.868	0.994	0.947	0.980	0.959	0.995	0.955	0.809
	D	0.407	0.434	0.511	0.470	0.562	0.546	0.454	0.727	0.540	0.365
2017	C	0.898	0.975	0.855	0.998	0.944	0.992	0.944	0.999	0.928	0.701
	D	0.421	0.432	0.565	0.469	0.578	0.531	0.442	0.721	0.575	0.330
2018	C	0.845	0.963	0.976	0.998	0.931	0.989	0.937	0.979	0.875	0.710
	D	0.379	0.430	0.644	0.450	0.574	0.529	0.439	0.650	0.600	0.353
2019	C	0.837	0.971	0.878	0.999	0.939	0.991	0.966	0.986	0.911	0.769
	D	0.383	0.429	0.589	0.435	0.578	0.532	0.459	0.677	0.578	0.377
2020	C	0.818	0.960	0.852	0.932	0.935	0.979	0.986	0.978	0.888	0.800
	D	0.372	0.430	0.559	0.525	0.591	0.544	0.479	0.632	0.598	0.386
2021	C	0.843	0.966	0.877	0.967	0.954	0.987	0.991	0.978	0.872	0.814
	D	0.381	0.425	0.594	0.495	0.582	0.531	0.483	0.641	0.620	0.387
2022	C	0.903	0.951	0.901	0.999	0.957	0.986	0.995	0.960	0.934	0.770
	D	0.418	0.443	0.637	0.442	0.621	0.560	0.512	0.701	0.584	0.388

Note: Mild disorder; On the verge of disorder; Marginal coordination; Primary coordination; Intermediate coordination

3.3 Characteristics of Coupling Coordination between Systems

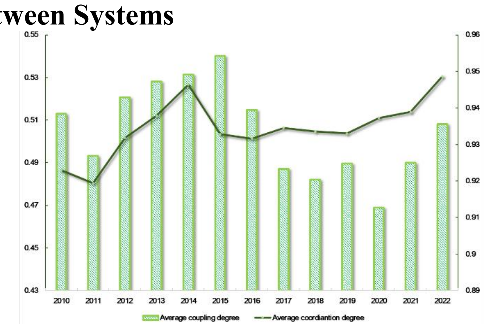
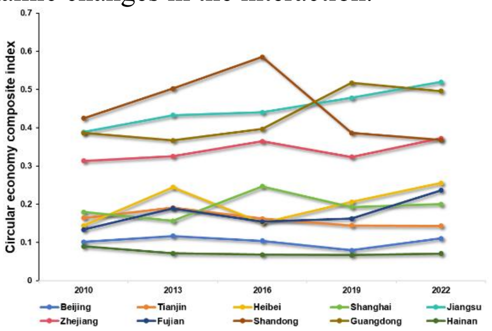


Figure 6. Trend plot of Time-series Evolution of Average Coupling and Coordination Degrees

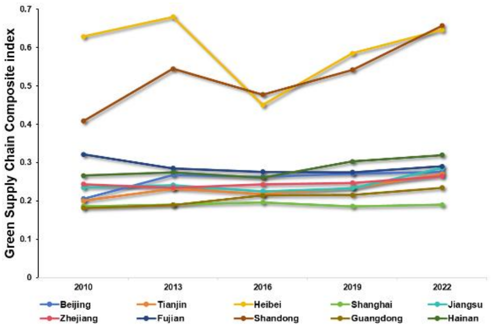
3.3.1 Coupling characteristics

The system coupling degree shows an increasing trend over time, indicating that the association between CE and GSC is deepening. As shown in Table 5, during the study period, the coupling degree of most provinces is from 0.800 to 1.000, with the average value as high as 0.934, which is in the stage of high coupling. Among them, Shanghai has the highest coupling degree (0.994), indicating that the development of CE and GSC shows almost the same trend of change. Each link of GSC provides resources input for CE, while the efficiency improvement of CE optimizes the GSC process in reverse, eventually forming a positive interaction. The coupling degree of Hainan is the lowest (0.784). The reason is that the two systems in Hainan are constrained by the contradiction between limited resources and development demand rigidity of the island-type economy from 2010 to 2016, which shows a phased reverse misalignment fluctuation.

As shown in Figure 6, the average coupling degree of the two systems generally shows a trend of rising, then falling, then rising, indicating that the correlation and interaction of the two systems have experienced a dynamic process of change in stages. As shown in Figure 7, the main reason is that the development of GSC in most provinces maintains stable growth, while the development of CE shows fluctuating and rising characteristics. The difference in the pace of development between the two leads to dynamic changes in the interaction.



a. CE



b. GSC

Figure 7. Composite Index Values for Provinces and Municipalities in 5 Years

Overall, the high level of coupling and the fluctuating upward trend reflect the coexistence of positive intersystem interactions and an uneven pace of development within the area.

3.3.2 Coordination characteristics

(1) Characteristics of temporal evolution

The coordination of the system continues to increase over time, indicating that the synergistic mechanism of CE and GSC is maturing. As shown in Table 5, the degree of coordination is generally at a medium level, ranging from 0.330 to 0.774, with a mean value of 0.506, which is at the stage of marginal coordination. As shown in Figure 6, the average annual growth rate of the coordination degree reaches 0.75%, and the area has gradually transitioned from the Dysfunctional Decline to Coordinated Elevation. Although they are generally on the rise, there is still room for improvement in the degree of coordination in most provinces and municipalities.

Although the development trend is positive, it is not sufficiently stable, reflecting a rhythmic difference between the policy push and the market response. The coordination degree of certain provinces is characterized by local fluctuations. For example, Hebei has seen a continuous increase in the degree of coordination in most years, but shows a downward trend in 2015 and 2016. This suggests that some provinces and municipalities are subject to external disturbance arising from policy changes. There is a phased imbalance in the coordination of the system, which requires the establishment of a more solid policy support mechanism.

(2) Characteristics of regional differences

Coordinated development leading regions are deeply dependent on their industrial base and resource advantages, with an initial degree of coordination of more than 0.5 in 2010 and an average annual growth rate of more than 1%. For example, Shandong, Hebei, Jiangsu, Guangdong, and Zhejiang are generally characterized by their resource advantages as large industrial provinces and the deep integration of green industrial chains. Among them, Shandong's coordination degree has been ranked first permanently. Its high level of coordination stems from its continuous expansion of the scale of resource utilization enterprises and its continuous strengthening of the development and application of renewable energy.

Coordinated development bottleneck regions reflect the long-term constraints of functional adjustment on the promotion of coordination. Their initial degrees of coordination are less than 0.5, and average annual growth rates are less than 1%. For example, Beijing, Tianjin, and Shanghai, in the context of provincial functional adjustment, the traditional path of synergy is difficult to replicate. There is an urgent need for them to explore new and more appropriate paths of integrated development. Among them, the deconcentration of Beijing's non-capital functions as a capital city may have distracted the green transformation momentum, creating a development bottleneck.

The guidance of policies plays a significant role in coordinated development catch-up regions with an initial degree of coordination less than 0.5 and an average annual growth rate greater than 1%. The development of industries limits their ability to coordinate and improve. Although Hainan and Fujian achieve growth under policy-driven guidance, the late start of CE and the insufficient volume of development limit their coordinated upgrading ability. Hainan has the tertiary industry as its leading industry, and the serious lack of CE-related enterprises affects its coordination degree.

4. Conclusions

This study selects data for a total of 13 years from 2010 to 2022, and analyses the synergistic development of CE and GSC in the eastern economic belt of China. It constructs a 3-layer system containing 17 indicators and combines EWM, TOPSIS, and CCDM to assess the performance of the degree of coupling coordination in 10 provinces and municipalities. It reveals the differences in the degree of coordination among them in the process of green transformation, which provides the direction and foundation for high-quality synergistic development.

On the theoretical level, this study enriches the theoretical framework of the synergy between CE and GSC based on the 3R principle of CE and the product life cycle theory of GSC. This study has constructed the analysis system of Input Reduction, Recycle and Reuse, and Pollution Minimization of CE, and Green Production, Green Logistics and Green Consumption of GSC. Then it has determined the corresponding indicators and evaluation methods, which provides a new analysis idea for the synergistic development of the two and further promotes the deepening of the concept of sustainable development.

In a practical sense, this study provides empirical evidence for the sustainable development of the eastern economic belt. It also provides decision-making references for the government and enterprises to promote GSC and CE synergy. It helps to realize the synergistic benefit of economic and green development. At the policy implementation level, the government needs to implement policy pilots based on the coupling and coordination features of regionalization in provinces and municipalities. For leading regions, such as Shandong, the government is expected to support them in leveraging their strengths by strengthening financial subsidies and tax incentives. Continuously promote its technological research and development and the renewal of advanced equipment to create industrial benchmarks. For bottleneck regions facing functional transformation, such as Beijing, set up government-supported special funds for green transformation. Encourage them to explore new paths of integrated development that fit the city's functional positioning and promote the innovation and upgrading of the traditional synergistic pattern. For catch-up regions with a weak foundation, such as Hainan, formulate special investment and cultivation policies for resource utilization enterprises. Guide the concentration of resources to enterprises to alleviate the problem of insufficient industrial volume. At the entrepreneurial level, it is necessary to deepen the integration of the technology of GSC and CE to form a positive closed loop of efficient resource utilization, supply chain optimization, and circular economy efficiency. For example, it is necessary to build a cross-enterprise collaborative management platform to achieve information sharing and business linkage between upstream and downstream supply chains and CE participants. Optimize the process to achieve greater efficiency in the use of resources in both, and to cope with market fluctuations and policy changes, thereby enhancing system coordination and stability.

Although the study has achieved phased achievements, there are still some limitations. On the one hand, the follow-up study can expand the scope of the study from the eastern economic belt to different areas of the country to carry out comparative analyses. On the other hand, the spatial and temporal evolution of the CE and GSC system can be explored in depth by combining spatial econometric models and other methods to analyze the pattern of change of synergistic development over time and space.

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