

Research on Spatiotemporal Evolution of Pollution & Carbon Reduction Synergy in Yangtze River Economic Belt and Multi - parties Governance Mechanism

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Abstract: This article is based on the non-radial Super SBM model and spatial econometric methods, combined with the Malmquist Luenberger index decomposition method, to systematically investigate the spatiotemporal evolution law and driving mechanism of the collaborative efficiency of pollution reduction and carbon reduction in the Yangtze River Economic Belt from 2013 to 2022. Research has found that: (1) Collaborative efficiency shows a "policy driven" ladder growth. After the implementation of the "Outline of the Development Plan for the Yangtze River Economic Belt" in 2016, the average annual growth rate changed from negative to positive (+3.15%), and the "dual carbon" target promoted the growth rate to 5.43%. The contribution rate of technological efficiency improvement to efficiency improvement reached 68.7%, confirming the leverage effect of policies on technology diffusion; (2) The spatial differentiation presents a "gradient convergence" feature, with downstream regions maintaining a leading position based on advanced industrial structure (service industry accounting for more than 45%) and green technology agglomeration (green patent density of 8.7 per 10000 people), midstream regions demonstrating policy resilience (shock resistance elasticity+0.12 σ), and upstream regions catching up through ecological compensation (average annual growth rate of 6.2%), but there is still a technology gap of 34%; (3) There is a non-linear interaction effect in multi-party governance. The government's green support increases the adoption rate of clean technologies by 0.38%/1% ($p<0.01$) through the "cost compensation" mechanism. However, in the early stage of transformation, equipment updates lead to a 12.7% rebound in carbon emissions, and there is a "behavioral response gap" in public participation. The marginal effect of online demands on actual emissions reduction is only 0.07% ($p>0.1$); (4) The spatial interaction presents a "double-edged sword" feature, with a spillover elasticity of 0.187 within a 300 kilometer radius of technology diffusion, while the "bottom-up competition" of environmental regulations leads to a 1% decrease in environmental intensity in neighboring areas and a 0.29% increase in local pollution emissions ($p<0.05$). At the theoretical level, a multi-party collaborative governance framework has been constructed to reveal the time-varying effects and spatial interaction boundaries of policy combinations; At the practical level, it is proposed to establish a governance system of "regional adaptation dynamic optimization spatial collaboration" and bridge the gap in public participation efficiency through digital technology. The research deepens the understanding of the stage characteristics and spatial spillover geographic laws of the green paradox, providing scientific basis for differentiated collaborative governance of the Yangtze River Economic Belt.

Keywords: Yangtze River Economic Belt; Collaborative efficiency of pollution reduction and carbon reduction; Non radial Super SBM model; Spatial Durbin model.

1. Introduction

As the core issue of environmental governance in the new era, the synergistic effect of pollution reduction and carbon reduction has gradually attracted widespread academic attention. The synergistic effect was originally used to describe the interactions in physical or chemical phenomena, as the existence of interdependent and cooperative relationships among various systems in the entire environment (Haken, 1973) [1], gradually expanding to the social and economic fields, and becoming an important concept in environmental management [2] (Weidlich, 1991; Margerum, R.D., 2008) [3]. Ayres and Walter (1991) [4] first proposed the concept of "co benefits" to illustrate the pollutant emission reduction effect brought about by greenhouse gas emissions reduction, while Pearce (1992) [5] further proposed the concept of "secondary benefits". The United Nations Climate Change Committee (IPCC) has clearly defined "synergies" in multiple assessment reports, applying it to multiple dimensions including the environment, economy, society, and the international community. Li Liping

et al. (2023) [6] pointed out that the environmental dimension is the foundation and goal of synergy, while the synergy of economic, social, and international dimensions can provide effective support and driving force for achieving environmental goals.

Research on pollution reduction, carbon reduction, and efficiency improvement both domestically and internationally mainly focuses on emission reduction effects, synergy, and cost control, and uses various evaluation models and methods. Foreign research is usually based on the energy economy environment system [7], using multi regional input-output models [8], mixed input-output models [9], greenhouse gas emission prediction and policy analysis models [10], long-term energy substitution planning systems [11], and computable general equilibrium models [12] to evaluate the benefits and costs of collaborative emission reduction. Meanwhile, domestic scholars have developed evaluation tools suitable for local conditions while using these models, such as the coordinate system method for collaborative control effects [13] and the evaluation index system [14]. In addition, double difference models [15], multi-objective

optimization models [16], life cycle assessment methods [17], and extended models based on KAYA identity [18] have also been used to evaluate synergistic effects. These evaluation tools quantitatively analyze the pollution reduction and carbon reduction effects in different regions and contexts, especially in terms of industrial structure optimization and regional economic development.

In the research on the factors affecting the synergistic effect of pollution reduction and carbon reduction, most studies focus on the analysis of the influencing factors of single pollutants or carbon emissions, and there is relatively insufficient research on the driving mechanism of the synergistic effect of the two. The influencing factors mainly include population, economy, technology, structure, and policies. Common analysis methods include IPAT model [19], Scalable Stochastic Environmental Impact Assessment (STRIPAT) model [20], Logarithmic Mean Dividing Index (LMDI) model [21], and Emission Concentration Response Surface Model [22]. Cui Lianbiao (2023) [23] conducted empirical analysis on the synergistic effect of pollution reduction and carbon reduction by combining DEA model and Tobit model, while Zhang Xuechun et al. (2023) [24] used the super efficiency SBM model and Tobit model to study the synergistic emission reduction efficiency of key urban agglomerations such as Beijing Tianjin Hebei and Yangtze River Delta. These studies provide a theoretical basis for understanding the driving mechanism of collaborative emission reduction, and also provide reference for future research to explore the implementation path of collaborative efficiency at a deeper level.

In terms of regional collaborative emission reduction, the Yangtze River Delta, Beijing Tianjin Hebei, and Guangdong Hong Kong Macao Greater Bay Area are key regions for China's pollution reduction and carbon reduction policies. Research has shown that there are significant differences in the implementation of synergies between different cities. For example, Wang Fei et al. (2024) [25] analyzed the spatiotemporal evolution of industrial pollution reduction and carbon reduction in the Yangtze River Delta region and found that due to differences in economic foundations and industrial structures among cities, there is a significant spatial imbalance in the implementation effect of collaborative emission reduction policies. The collaborative emission reduction analysis in the Beijing Tianjin Hebei region further reveals the low coupling and instability of the synergistic effect between carbon dioxide and atmospheric pollutants, indicating that differentiated policy tools and strategies between regions are of great significance for achieving collaborative goals.

In order to measure the synergistic efficiency of pollution reduction and carbon reduction, most studies have adopted methods such as data envelopment analysis (DEA) model and spatial Durbin model. For example, Liu Mingliang et al. (2024) [26] evaluated the collaborative efficiency of the three major urban agglomerations of Beijing Tianjin Hebei, Yangtze River Delta, and Pearl River Delta through super efficiency SBM and spatial Durbin model. The results showed that although the overall pollutant and carbon emissions decreased, the collaborative efficiency of each urban agglomeration was influenced by multiple factors such as industrial structure, policy intervention intensity, and economic openness level, and there were significant differences.

In recent years, research on collaborative pathways for

pollution reduction and carbon reduction has gradually increased, especially at the level of urban agglomerations and industries, exploring specific paths and effects of policy implementation. For example, Zhu Siyu et al. (2023) [32] studied the different effects of policy tools in core and peripheral cities in the Yangtze River Delta region, and found that the effectiveness of policies varies depending on the regional economic foundation and industrial characteristics. In addition, Guo Pei and Wang Guangyuan (2023) [33] explored the promoting effect of digital economy on pollution reduction and carbon reduction, and believed that the industrial transformation of digitalization and intelligence can effectively enhance the synergistic effect. The above research provides empirical support for formulating more targeted regional emission reduction policies.

In summary, research on the synergistic effect of pollution reduction and carbon reduction both domestically and internationally covers multiple aspects, including theoretical foundations, evaluation models, influencing factors, regional collaborative cases, efficiency evaluation, and path exploration, and has made significant progress. However, there are still shortcomings in the existing literature regarding regional differentiation policies and further optimization of collaborative control pathways. This study aims to systematically evaluate the synergistic effects of pollution reduction and carbon reduction in the Yangtze River Delta urban agglomeration by combining DEA and spatial Durbin model. It conducts in-depth analysis from the aspects of collaborative emission reduction of pollutants and carbon dioxide, collaborative efficiency of each city, and policy scenario simulation, in order to fill the research gap, provide more comprehensive and scientific policy support, and provide theoretical guidance and practical reference for the green and low-carbon development of the Yangtze River Delta region.

2. Theoretical Hypotheses and Data

2.1. Single Agent, Multiple Agents and the Synergistic Efficiency of Pollution Reduction and Carbon Emission Reduction

Reducing pollution and carbon emissions is a complex and systematic task that requires the participation of multiple stakeholders to achieve collaborative governance. The role of a single entity in governance is relatively limited: as a policy maker and regulatory body, the government constrains pollution behavior through legislation, financial subsidies, and technical standards, but its governance efficiency may be limited due to information asymmetry, limited resources, and difficulty in policy implementation. As the main source of carbon and pollutant emissions, enterprises play an irreplaceable role in technological innovation, resource integration, and emission reduction practices. However, economic goals driven by interests may weaken their environmental responsibility. Public participation is reflected in behavior change, environmental supervision, and policy support, but the lack of public organization and limited technology and resources result in limited independent effectiveness.

In contrast, multi-party collaboration can form significant synergistic effects in pollution reduction and carbon reduction governance. According to the theory of collaborative governance, the government, enterprises, and the public can

improve governance efficiency through resource integration and functional complementarity. The government guides enterprises to adopt green technologies and fulfill environmental responsibilities by improving policy frameworks and economic incentives, while using publicity and guidance to stimulate public participation in governance. Under policy promotion, enterprises are integrating green transformation into their production and operation, reducing emissions and improving resource utilization efficiency. The public plays an important role in supervising enterprises and providing feedback on the effectiveness of policy implementation, further enhancing governance transparency and sense of responsibility.

The advantage of multi-party collaboration is that it compensates for the shortcomings of a single entity governance model, enables collaborative control of pollutants and greenhouse gas emissions, and enhances regional governance effectiveness. Therefore, the following hypothesis H1 is proposed:

H1: The multi subject collaborative governance model is significantly better than single subject governance, and can effectively improve the collaborative efficiency of regional pollution reduction and carbon reduction.

2.2. Government Green Technology Support and the Synergy Efficiency of Pollution Reduction and Carbon Abatement

The government's support for green technology is an important guarantee for promoting the improvement of the synergy efficiency of pollution reduction and carbon abatement. Based on the theory of ecological modernization, green technology innovation is regarded as a key way to resolve the contradiction between environmental issues and economic growth. As an important driving force for the research, development, and promotion of green technologies, the government can achieve the publicity and systematicness of technological progress through policy tools. Specifically, the government can reduce the research and development costs of green technologies and promote the diffusion and application of new technologies by providing financial subsidies, setting up research and development funds, and implementing green tax incentives. Meanwhile, the government guides enterprises to increase the adoption rate of green technologies through environmental regulations, promoting the transformation of enterprises from traditional high - pollution production methods to clean production methods.

In addition, the mechanism of the government's support for green technology is diverse. On the one hand, the research, development, and application of green technologies can directly reduce pollutant and greenhouse gas emissions, achieving the goal of collaborative governance. On the other hand, the support for green technology affects the choice of technological paths and the improvement of production efficiency of enterprises, realizing a win - win situation for the economy and the environment. However, the effect of green technology support depends largely on the cooperation of enterprises and the public. Whether enterprises actively respond to policy incentives and whether the public accepts green products and technologies will directly affect the efficiency of the promotion of green technologies. Therefore, the following hypothesis H2 is proposed:

H2: Under the multi - subject collaborative governance model, the subjects increase the intensity of the government's

support for green technology to significantly improve the synergy efficiency of pollution reduction and carbon abatement.

2.3. Enterprise Green Transformation and the Synergistic Efficiency of Pollution Reduction and Carbon Emission Reduction

The green transformation of enterprises is an important link in the coordinated governance of pollution reduction and carbon reduction, and it is also the core driving force for achieving the coordination and unity of environmental goals and economic goals. Based on the theory of sustainable development, enterprises can significantly reduce pollutant and greenhouse gas emissions by applying clean production technologies, optimizing production processes, and recycling resources, thereby improving production efficiency while reducing environmental burdens. The core of green transformation lies in the transformation of enterprises from traditional linear economic models to low-carbon, circular, and green economic models, achieving the unity of pollution reduction and efficient utilization of resources.

The driving force for corporate green transformation comes from both internal and external pressures. On the one hand, the government forces enterprises to fulfill their environmental responsibilities through environmental regulations and market-oriented means, promoting green innovation in technology research and production practices; On the other hand, the supervision of the public and the environmental preferences of consumers also encourage enterprises to adopt greener business models to enhance market competitiveness and public recognition. In addition, there is a significant synergistic effect between corporate green transformation and government green technology support: government driven green technology research and development and technology diffusion provide enterprises with more optional green technology solutions, while corporate transformation practices further promote the marketization and expansion of the application scope of green technology. Therefore, the following hypothesis H3 is proposed:

H3: Under the multi-agent collaborative governance model, the main body promotes the green transformation of enterprises to significantly improve the collaborative efficiency of pollution reduction and carbon reduction.

2.4. The Significant Spatial Spillover Effects of Multi - parties Collaborative Governance

The spatial spillover effect of multi-agent collaborative governance stems from the cross regional mobility of environmental issues and the interactive impact of governance actions. According to the spatial dependence theory and competition theory, the governance behavior of a certain region not only affects local efficiency, but also has asymmetric effects on neighboring regions through channels such as material circulation, policy imitation, and technology diffusion. The specific mechanism is as follows: green technology research and development achievements supported by the local government (such as sewage treatment patents and clean energy technologies) can be disseminated to neighboring regions through enterprise cooperation, academic exchanges, and other channels to improve overall emission reduction efficiency [36]. Successful multi-party

collaborative governance models, such as the Yangtze River Delta ecological compensation mechanism, may be borrowed by neighboring regional governments to promote policy convergence and governance standards unification between regions. The green supply chain demand formed by the green transformation of downstream enterprises (such as low-carbon raw material procurement) forces upstream supplier enterprises to upgrade their technology and form cross regional industrial synergy.

H4: Multi subject collaborative governance has significant spatial spillover effects.

2.5. Data

In December 2013, the National Development and Reform Commission held a report meeting on the construction of the Yangtze River Economic Belt in Beijing, reviewing the overall reports and six special achievements of various provinces and cities. This meeting expanded the Yangtze River Economic Belt from the original 9 provinces and cities to 11 provinces and cities, adding Zhejiang and Guizhou, and established a major strategic decision to rely on the golden waterway to promote the development of the Yangtze River Economic Belt and create a new support belt for the Chinese economy. Considering the expansion of cities in the Yangtze River Economic Belt and to ensure the accuracy of the research scope, 2013 has been determined as the starting point for the study; Considering the integrity of the data, the endpoint of the study is determined to be 2022. This article selects panel data from 11 provinces and cities in the Yangtze River Economic Belt from 2013 to 2022 as the research

$$\ln ser_{it} = \alpha + \beta_1 \ln gti_{it} + \beta_2 \ln egt_{it} + \beta_3 \ln pe_{it} + \gamma C_{it} + \mu_i + \lambda_t + \delta_{it} \quad (1)$$

Among them, ser_{it} represents the collaborative emission reduction efficiency of province i in year t (in natural logarithmic form). Core explanatory variable: $\ln gti_{it}$ represents the government's support for green technology in province i in year t (logarithmized), used to measure the degree of government participation in governance. The green transformation intensity of $\ln egt_{it}$ enterprises in province i in year t is used to measure the degree of enterprise participation in governance. $\ln pe_{it}$ Express the degree of public participation in province i in year t (logarithmic),

$$\ln ser_{it} = \alpha + \beta_1 \ln egt_{it} + \beta_2 \ln gti_{it} + \beta_3 (\ln egt \times \ln gti)_{it} + \gamma C_{it} + \mu_i + \lambda_t + \delta_{it} \quad (2)$$

In order to reduce multicollinearity, following Aiken's approach, the continuous variables $\ln egt_{it}$ and $\ln gti_{it}$ were centralized, and the moderating effect was tested through the interaction coefficient test, indicating that government support positively regulates the synergistic emission reduction effect of enterprise transformation.

3.3. Spatial Durbin Model

After verifying the local synergy effect of multi-agent participation (moderation effect model), further investigation of its spatial interaction mechanism is needed. The moderation effect model reveals the local strengthening effect of government support (GTI) on corporate green transformation (EGT), but fails to capture the geographical diffusion characteristics of policy effects. To comprehensively analyze the cross regional collaborative

sample for analysis. All data comes from the China Statistical Yearbook, China Environmental Yearbook, and China Energy Statistical Yearbook. The annual PM2.5 concentration data is sourced from the data released by Washington University in St. Louis. Partial missing values were filled using linear interpolation. Considering collinearity and dimensional issues, some variables were logarithmically processed. The variable description and statistical analysis are shown in Table 1:

Table 1. Descriptive Statistics of Variables

Variable	Obs	Mean	S. D.	Min	Max
lnser	110	-0.9956	0.5211	-2.1881	0.0384
ln tec	110	4.7693	0.5001	3.5673	5.5021
pe	110	0.3128	0.1299	0.0808	0.7526
ln pd	110	-3.2597	0.8239	-4.4136	-1.2115
ln egt	110	5.3097	0.8988	3.2023	7.6657
gti	110	0.2659	0.1794	0.0216	0.9109
ln edl	110	11.3382	0.3721	10.7570	12.1196
ln is	110	9.4882	0.7772	8.1750	11.0269
ln ur	110	-0.5220	0.2045	-0.9705	-0.1010

3. Research Methods

3.1. Benchmark Regression Model

To test the direct impact of multi-agent participation on collaborative emission reduction efficiency (SER), a bidirectional fixed effects panel model was constructed to control for individual and time effects.

quantified by the number of environmental complaint cases. C_{it} Representing control variables; μ_i and λ_t respectively represent individual effects and time effects; δ_{it} represents a random perturbation term; β_i and γ the regression coefficient representing the variable.

3.2. Moderating Effect Model

To test the moderating effect of government green support (GTI) on the emission reduction effect of enterprise green transformation (EGT), the following interaction effect model is constructed:

mechanism involving multiple parties, it is necessary to introduce the spatial Durbin model to study the spatial dependence and spillover channel heterogeneity of collaborative emission reduction efficiency in different regions.

Before constructing a spatial model, it is necessary to test the spatial autocorrelation of the dependent variable (collaborative emission reduction efficiency). Using the Global Moran's I index, the calculation formula is shown in formula (3):

$$I = \frac{N}{\sum w_{ij}} \cdot \frac{\sum w_{ij} (y_i - \bar{y})(y_j - \bar{y})}{\sum (y_i - \bar{y})^2} \quad (3)$$

Among them, N is the number of provinces, w_{ij} is the element of the spatial weight matrix, uses the geographic adjacency matrix as the spatial weight matrix, y_i is the

collaborative emission reduction efficiency of provinces i , and \bar{y} is the global mean. If $I > 0$, the significance test ($p < 0.05$) indicates the existence of spatial positive correlation, a spatial model should be used.

$$\ln ser_{it} = \rho W \ln ser_{jt} + \beta X_{it} + \theta W X_{jt} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

Among them, $\ln ser_{it}$ represents the collaborative emission reduction efficiency of the province i in the year t (logarithmic). X_{it} representing spatial autoregressive coefficients, reflecting the spillover effects of neighboring region efficiency on the local area. Representing explanatory variable vectors, including $\ln gti_{it}$, $\ln egt_{it}$, $\ln pe_{it}$, and control variables. β Indicate the direct effect coefficient of local variables. $W = [w_{ij}]$ representing the coefficient of explanatory variables for spatial lag, capturing the indirect impact of behavior in neighboring regions. The spatial weight matrix is constructed based on the geographic adjacency matrix and standardized to meet the following requirements $\sum_j w_{ij} = 1$. μ_i, λ_t : fixed effects of province and year, controlling for unobservable spatiotemporal heterogeneity.

4. Empirical Analysis

4.1. Quantitative Evaluation of Synergistic Effects of Pollution Reduction and Carbon Reduction

The synergistic efficiency of pollution reduction and carbon reduction in the Yangtze River Economic Belt from 2013 to 2022 was calculated using Super SBM, and the results are shown in Figure 1. The figure shows the changing trend of collaborative emission reduction efficiency in the Yangtze River Economic Belt and its upstream and downstream regions from 2012 to 2022, presenting significant regional differences and temporal evolution characteristics. From the perspective of time evolution, 2016 is an important turning point for the accelerated growth of collaborative emission reduction efficiency. This is closely related to the promulgation of the Outline of the Development Plan for the Yangtze River Economic Belt. Under the guidance of this outline, governments at all levels have taken a series of measures in watershed ecological governance, industrial green transformation, and technological innovation, providing strong policy support for the improvement of collaborative efficiency. In addition, the significant increase in collaborative emission reduction efficiency after 2020 is closely related to the proposal of the "dual carbon" target. Against the backdrop of accelerating global carbon neutrality, the Communist Party of China put forward the "14th Five Year Plan" development goals at the Fifth Plenary Session of the 19th Central Committee of the Communist Party of China, including more rational allocation of energy resources, significant improvement in utilization efficiency, accelerating the promotion of green and low-carbon development, reducing carbon emission intensity, supporting regions with conditions to take the lead in reaching carbon emission peaks, and formulating action plans for peaking carbon emissions before 2030. This provides important impetus for improving the coordinated emission reduction efficiency of the Yangtze River Economic Belt. It is worth noting that 2020 is the intersection point of collaborative emission reduction efficiency between the midstream and upstream regions. During the COVID-19, Wuhan, the core city in the middle

After conducting a global autocorrelation test, in order to further investigate the spatial spillover effects of heterogeneous environmental regulations on the synergistic effects of pollution reduction and carbon reduction, a spatial Durbin model was constructed as shown in formula (4):

reaches of the region, suffered heavy economic losses and industrial production and logistics were blocked, which directly led to the slowdown of the growth of synergy efficiency in the region or even stagnation in the short term. The upstream regions, on the other hand, have shown more significant efficiency improvements due to relatively dispersed economic activities, lower industrial intensity, less negative impact from the epidemic, and greater policy support.

Despite the overall trend of collaborative efficiency, there are significant differences in the level and growth rate of collaborative emission reduction efficiency between different regions: the collaborative emission reduction efficiency of downstream regions has always been in a leading position, with efficiency values even approaching 1 after 2020. This is mainly due to the strong economic foundation and optimized industrial structure in downstream areas, as well as their high technological level and policy implementation capabilities. As a highly developed economic region, downstream areas have significant advantages in environmental technology research and development, green industry development, and resource conservation and utilization, which can achieve a win-win situation between pollutant reduction and economic development faster. At the same time, downstream regions have a strong sensitivity to environmental policies and respond quickly to them, laying a solid foundation for improving collaborative efficiency. The collaborative emission reduction efficiency in the midstream region ranks in the middle, and its growth rate is relatively stable. However, in 2020, there was an efficiency intersection with the upstream region, which is closely related to the fact that Wuhan, the core city in the middle reaches, was seriously impacted by the COVID-19. As the core of the economy and population in the midstream region, Wuhan's economic activities have been significantly affected by the epidemic, and the significant slowdown in industrial production and economic activities may have had a certain negative impact on the efficiency of collaborative emission reduction. Nevertheless, the midstream region has gradually recovered after the epidemic, thanks to the support of the national "green recovery" policy, and its synergistic efficiency has returned to the growth track after 2021. The collaborative emission reduction efficiency in upstream regions started relatively low, but the growth rate was the largest, especially showing a significant catch-up trend after 2020.

This phenomenon indicates that upstream regions have made breakthrough progress in environmental policy support and green transformation. As a region where resource-based and energy based industries are concentrated, upstream areas have increased investment in industrial restructuring, introduction of green technologies, and environmental governance capacity building in recent years. In addition, with the tilted support of central policies, the efficiency of pollution control and carbon reduction in upstream regions has significantly improved, narrowing the gap with middle and downstream regions.

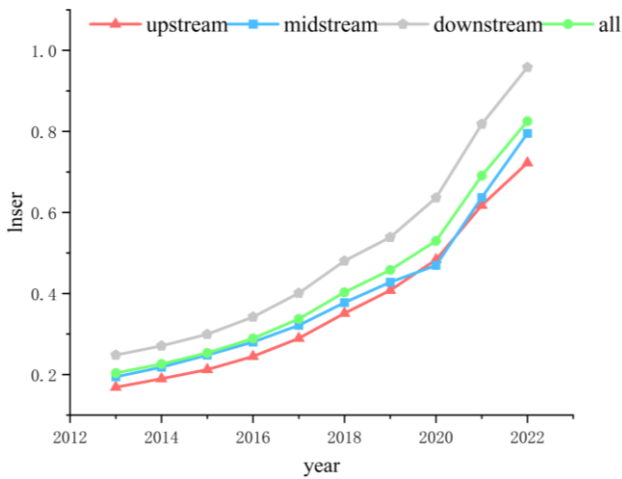


Figure 1. Collaborative Efficiency of Pollution Reduction and Carbon Reduction in the Yangtze River Economic Belt from 2013 to 2022

4.2. Benchmark Regression Analysis

Based on the Hausman test results (all rejecting null and false), this study established a two-way fixed effects model for benchmark regression analysis. The results are shown in Table 2, systematically examining the differential effects of government green support (GTI), enterprise green transformation (EGT), and public participation (PE) on the synergistic efficiency of pollution reduction and carbon reduction (SER). The results indicate that the role of multi-party participation in collaborative emission reduction exhibits significant heterogeneity and is deeply influenced by regional development characteristics and policy tool synergy. In model (1), the coefficient of government green support is 0.070 ($p < 0.1$), indicating that for every 1% increase in government investment in green technology, the collaborative emission reduction efficiency improves by 0.070%. This positive effect confirms the H1 hypothesis, indicating that policy tools such as fiscal subsidies and tax incentives can effectively guide enterprises to upgrade their technology. However, when included together with other subject variables in model (4), the coefficient decreased to 0.044 and was no longer significant, indicating that the independent role of government support may be partially absorbed by the interaction effect between corporate transformation and public participation, and further analysis of policy synergy is needed through a moderation effect model.

In Model (2), the green transformation coefficient of enterprises is -0.143 ($p < 0.05$), indicating that for every 1% increase in pollution control investment, the collaborative emission reduction efficiency decreases by 0.143%. This 'green paradox' may stem from two aspects: firstly, equipment updates and shutdowns during the early stages of transformation leading to a short-term rebound in pollution emissions; Secondly, environmental investment squeezes research and development funds, inhibiting long-term green innovation (such as the EGT coefficient in model (4) still being negative but not significant). This is consistent with Porter's hypothesis of non-linear relationships, indicating that "following cost effects" dominates in the early stages of transformation.

In model (3), the coefficient of public participation is -0.097 ($p < 0.01$), and for every 1% increase in public environmental complaints, the collaborative efficiency decreases by 0.097%. This result challenges the traditional perception of "public supervision promoting emission

reduction" and reflects the structural defects of the current participation mechanism: on the one hand, complaint based participation exacerbates the game between government and enterprises, inducing strategic emission reduction by enterprises (such as data fraud); On the other hand, public environmental awareness has not yet been transformed into substantive low-carbon behavior, and environmental governance is still in the stage of "end of pipe control".

Table 2. Benchmark Regression Results

	(1)	(2)	(3)
	Inser	Inser	Inser
lngti	0.070*		
	(1.902)		
lnegt		-0.143**	
		(-2.049)	
lnpe			-0.097***
			(-2.764)
lnedl	0.893	0.933	0.704
	(1.104)	(1.051)	(0.855)
lnpd	-0.134	-0.371	-0.018
	(-0.257)	(-0.723)	(-0.034)
intec	-0.432***	-0.452***	-0.506***
	(-3.487)	(-3.779)	(-4.287)
lnis	0.433***	0.428***	0.437***
	(3.497)	(3.790)	(3.751)
lnur	0.315***	0.371***	0.258***
	(2.941)	(3.236)	(2.971)
Cons	-13.327	-13.738	-10.753
year	YES	YES	YES
province	YES	YES	YES
	(-1.385)	(-1.302)	(-1.101)
N	110.000	110.000	110.000
r2	0.987	0.987	0.988

Note: ***, **, and * respectively indicate significance at the 1%, 5%, and 10% levels, with t-values in parentheses. (Same below)

4.3. Regulating Effect

Based on the theory of ecological modernization and the perspective of policy synergy, government green technology support (lngti) not only directly affects emission reduction efficiency in environmental governance, but also may form a "policy technology" synergy mechanism by regulating the effect of enterprise green transformation (lnegt). The theoretical logic of this regulatory effect is that the government reduces the technological risks and cost thresholds for enterprise transformation through policy tools such as green technology research and development funding and intellectual property protection, thereby amplifying the marginal contribution of enterprise green innovation to emission reduction efficiency. In empirical research, the significant positive coefficient (0.174, $p = 0.001$) of the interaction term ($lngt \times lnegt$) indicates that for every 1 unit increase in government support, the emission reduction effect of enterprise transformation increases by 17.4%. This discovery echoes the governance logic of "policy empowering the market", revealing that the synergistic effect between the government and enterprises is the key path to breaking through the limitations of single subject governance, and provides a theoretical basis for the design of "technology

driven" environmental policies in the Yangtze River Economic Belt.

Table 3. Adjustment Effect Results

	(1)
	Inser
lnegt	0.457*** (0.088)
lngti	-0.766*** (0.275)
interaction	0.174*** (0.049)
lnpd	4.115*** (1.553)
lnedl	-3.438*** (1.017)
lntec	0.842*** (0.306)
lnis	1.340*** (0.334)
lnur	0.149 (0.275)
Cons	32.495*** (12.088)
N	110
R ²	0.8364
F	58.17

4.4. Regional Heterogeneity Analysis

The regression results by region show significant spatial heterogeneity in the impact of government support on collaborative emission reduction efficiency. In the midstream region, the GTI coefficient is 0.161 (t=2.04, p<0.05), indicating that for every 1% increase in green technology

investment by the government, the collaborative emission reduction efficiency in the region can be improved by 0.161%, verifying the effectiveness of policy resource allocation towards industrial agglomeration areas. However, the GTI coefficients for upstream and downstream regions were -0.060 (p>0.1) and -0.064 (p>0.1), respectively, and the statistics were not significant, indicating that the traditional fiscal subsidy model has policy failures in ecologically fragile areas and highly urbanized areas, which may be due to technological diffusion barriers or lack of market incentive mechanisms. The EGT coefficient in the midstream region is significantly negative (-0.228, t=-2.42, p<0.05), indicating that for every 1% increase in pollution control investment by enterprises, the emission reduction efficiency decreases by 0.228% in the short term. This is consistent with the prediction of the "Green Paradox" [47]: the transformation of traditional industries, accompanied by high equipment renewal and capacity adjustment costs, may weaken the current emission reduction motivation of enterprises. On the contrary, the EGT coefficients in the upstream and downstream regions did not pass the significance test ($|t| < 1$), indicating that their transformation process has not yet crossed the inflection point of the "Environmental Kuznets Curve" [48], and the application of emission reduction technologies is still in its infancy. The PE coefficient in the upstream region is -0.096 (t=-2.18, p<0.05). For every 1% increase in public environmental demands, the emission reduction efficiency decreases by 0.096%, revealing the existence of an environmental rebound effect in the ecological barrier zone: excessive public intervention in ecological protection may trigger local governments to relax environmental regulations to balance economic growth (Li et al., 2020). However, the PE coefficient in the middle and lower reaches is not significant (p>0.1), indicating that the effectiveness of public participation is limited by the lack of information transparency and insufficient development of social organizations.

Table 4. Regional Heterogeneity Analysis

	upstream			midstream			downstream		
	Inser	Inser	Inser	Inser	Inser	Inser	Inser	Inser	Inser
lngti	-0.0604 (-1.47)			0.161 -2.04			-0.0639 (-0.69)		
lnegt		-0.0151 (-0.19)			-0.228* (-2.42)			0.00632 -0.08	
lnpe			0.0959* (-2.18)			-0.0829 (-0.87)			-0.0477 (-0.72)
cons	-28.08* (-2.82)	-33.01** (-3.13)	-24.84* (-2.76)	18.88 -0.89	-0.373 (-0.02)	11.92 -0.42	-47.67 (-1.62)	-44.01 (-1.45)	-45.56 (-1.61)
controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
year	YES	YES	YES	YES	YES	YES	YES	YES	YES
province	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	40	40	40	30	30	30	40	40	40
R ²	0.996	0.996	0.997	0.992	0.993	0.989	0.996	0.995	0.996

4.5. Analysis of Spatial Spillover Effects

By conducting a global Moran index test on the synergistic effects of pollution reduction and carbon reduction in the Yangtze River Economic Belt from 2013 to 2022, the spatial trend was studied. The results are shown in Table 5. The

global Moran's index is all greater than 0 and shows a fluctuating trend. The index can reject the null hypothesis at a significance level of 5%. The synergistic effect of pollution reduction and carbon reduction in the Yangtze River Economic Belt exhibits significant spatial dependence.

Table 5. Global Moran Index

year	2013	2014	2015	2016	2017
Moran's I	0.420 (2.747)***	0.412 (2.668)***	0.404 (2.615)***	0.395 (2.545)***	0.385 (2.493)***
year	2018	2019	2020	2021	2022
Moran's I	0.352 (2.325)***	0.290 (2.001)***	0.364 (2.231)***	0.321 (2.194)***	0.279 (1.917)***

Table 6 reports the statistical test results of the spatial econometric model selection, which systematically verifies the scientificity and robustness of the model settings. Firstly, the spatial dependence test showed that both the spatial error model and the spatial lag model passed the 1% significance test, and the robust LM test further supported the dominance of spatial error effects (Robust LM_Spatial-error=21.189, $p < 0.01$). Secondly, both the Wald test (Wald_Spatial_lag=96.49, $p < 0.01$) and the LR test (LR_Spatial_lag=70.66, $p < 0.01$) significantly rejected the null hypothesis that the SDM model can be simplified to SAR or SEM, confirming the necessity of setting up a spatial Durbin model (SDM). The Hausman test ($p < 0.01$) strongly supports the bidirectional fixed effects model, which controls for unobservable provincial heterogeneity and temporal trends. In addition, the time fixed effects LR test (LR_Spatial_time=39.6, $p < 0.01$) confirmed the need to control for annual macro shocks. In summary, this study chose the bidirectional fixed effects SDM model, which simultaneously captures the spatial autocorrelation of the dependent variable and the cross regional spillover of the explanatory variable, providing an optimal estimation framework for identifying spatial interaction mechanisms involving multiple parties.

Table 6. Selection of Spatial Econometric Models

statistical test	statistic
LM_spatial_error	46.045***
LR_spatial_ind	70.56***
LM_spatial_lag	31.15***
Robust LM spatial error	21.189***
Robust LM spatial lag	6.294**
Wald_spatial_error	70.56***
Wald_spatial_lag	96.49***
Hausman test	70.56***
LR_spatial_time	39.6***
LR_spatial_error	70.06***
LR_spatial_lag	70.66***

The coefficients of local enterprise green transformation (Inegt) in models (1) and (4) are 0.082 ($t=3.412$, $p < 0.01$) and 0.096 ($t=3.885$, $p < 0.01$), respectively, indicating that for every 1% increase in green transformation investment by the enterprise, the local collaborative emission reduction efficiency increases by 0.082% and 0.096%, respectively, verifying the local effectiveness of green technology application [45]. However, the coefficient of its spatial lag term ($W * Inegt$) is negative (-0.067 to -0.073) and not significant ($t < -1.5$, $p > 0.1$), suggesting that the transformation of neighboring enterprises may suppress the improvement of local emission reduction efficiency through factor competition effects (such as talent siphoning) [46]. The coefficient of local public participation (Inpe) is significantly positive (0.048-0.054, $t > 2.6$, $p < 0.01$), but the coefficient of spatial lag term ($W * Inpe$) is not significant and the direction is unstable (Model 2: 0.113 vs. Model 4: -0.042), reflecting the existence of geographical boundary effects in public

environmental supervision: local environmental actions are difficult to transmit across regions, and excessive public intervention in neighboring areas may trigger local protectionism and weaken the willingness for collaborative governance. The coefficient of local government support (Ingti) is 0.113-0.121 ($t > 2.2$, $p < 0.05$), and its spatial lag term ($W * Ingti$) is significantly positive (0.088-0.091, $t \approx 1.97$, $p < 0.1$), indicating that there is a technology diffusion dividend in government policies: for every 1% increase in green technology investment in neighboring areas, local efficiency can be improved by 0.09% through knowledge spillover and policy imitation, which is in line with the "policy learning theory" (Shipan & Volden, 2008).

Table 7. Double Fixed Space Durbin Regression Results

	(1)	(2)	(3)	(4)
Inegt	0.082*** (3.412)			0.096*** (3.885)
Inpe		0.054*** (2.987)		0.048*** (2.673)
Ingti			0.121*** (2.357)	0.113*** (2.241)
W*Inegt	-0.067 (-1.582)			-0.073 (-1.734)
W*Inpe		0.113 (-1.205)		-0.042 (-1.217)
W*Ingti			0.088* (1.953)	0.091* (1.972)
Inpd	-0.213 (-1.432)	-0.185 (-1.287)	-0.197 (-1.315)	-0.224* (-1.823)
Inedl	0.634*** (2.234)	0.587*** (2.115)	0.602*** (2.087)	0.618 (2.154)
Intec	0.327*** (3.875)	0.352*** (4.012)	0.341*** (3.956)	0.335*** (3.892)
Inis	0.418*** (5.672)	0.402*** (5.421)	0.427*** (5.723)	0.409*** (5.512)
Inur	0.195*** (3.214)	0.173*** (2.987)	0.182*** (3.052)	0.188*** (3.127)
W*Inpd	-1.874* (-1.823)	-1.792* (-1.765)	-2.013** (-2.215)	-1.927** (-2.103)
W*Inedl	0.756* (1.872)	0.718* (1.815)	0.732* (1.803)	0.741* (1.842)
W*Intec	0.214 (1.132)	0.193 (1.057)	0.207 (1.104)	0.198 (1.087)
W*Inis	0.358** (2.315)	0.327** (2.187)	0.341*** (2.254)	0.333*** (2.198)
W*Inur	-0.427** (-2.234)	-0.403** (-2.157)	-0.415** (-2.198)	-0.421** (-2.215)
ρ	0.312** (2.214)	0.287** (2.087)	0.295** (2.134)	0.302** (2.173)
sigma2_e	0.001*** (10.327)	0.001*** (10.415)	0.001*** (10.385)	0.001*** (10.402)
N	110	110	110	110
R ²	0.572	0.538	0.553	0.561

The coefficient of local economic development (Inedl) is significantly positive (0.587-0.634, $t > 2.1$, $p < 0.05$), but its spatial lag term ($W * Inedl$) coefficient is 0.718-0.756 ($t \approx 1.8$,

$p < 0.1$), indicating that economic expansion in neighboring regions promotes local emissions reduction through demand spillover effects (such as green product market sharing), verifying the environmental synergy benefits of regional economic integration. The coefficient of local population density (lnpd) is negative (-0.213 to -0.224, $t \approx -1.8$, $p < 0.1$), and the coefficient of spatial lag term ($W * \lnpd$) is significantly negative (-1.792 to -2.013, $t < -1.76$, $p < 0.05$), indicating that the population agglomeration area is facing resource overload pressure, and the population growth in neighboring areas intensifies environmental carrying capacity competition (such as water resource competition), forming a "dual resource curse". The coefficient of local urbanization (lnur) is significantly positive (0.173-0.195, $t > 2.9$, $p < 0.01$),

but its spatial lag term ($W * \lnur$) coefficient is -0.403 to -0.427 ($t \approx -2.2$, $p < 0.05$), revealing the risk of regional polarization in urbanization: urbanization in neighboring areas may inhibit local green infrastructure investment through capital and policy resource siphoning.

To ensure the credibility of the empirical results, this paper conducted robustness tests by replacing the spatial weight matrix, and the results are shown in Appendix 8. Model (1) is constructed using a geographic distance weight matrix, while Model (2) is constructed based on an economic distance matrix. From the table, the main explanatory variables and spatial correlation coefficients are consistent and significant with the regression results of the benchmark model, indicating the reliability of the empirical results in this paper.

Table 8. Robust Test Results

	-1	-2		-1	-2
lnegt	0.096***	0.099***		-5.512	-5.554
	-3.885	-3.962	lnur	0.188***	0.191***
lnpe	0.048***	0.051***		-3.127	-3.153
	-2.673	-2.785	$W * \lnpd$	-1.927**	-1.823**
lngti	0.113***	0.116***		(-2.103)	(-2.014)
	-2.241	-2.318	$W * \lnedl$	0.741*	0.715*
$W * \lnegt$	-0.073	-0.062		-1.842	-1.778
	(-1.734)	(-1.627)	$W * \text{Intec}$	0.198	0.184
$W * \lnpe$	-0.042	-0.038		-1.087	-1.058
	(-1.217)	(-1.084)	$W * \lnis$	0.333***	0.319***
$W * \text{lngti}$	0.091*	0.097*		-2.198	-2.173
	-1.972	-1.891	$W * \lnur$	-0.421**	-0.404**
lnpd	-0.224*	-0.219*		(-2.215)	(-2.172)
	(-1.823)	(-1.798)	ρ	0.302**	0.290**
lnedl	0.618***	0.632***		-2.173	-2.146
	-2.154	-2.187	sigma2_e	0.001***	0.002***
Intec	0.335***	0.340***		-10.402	-10.359
	-3.892	-3.927	N	110	110
lnis	0.409***	0.414***	R ²	0.561	0.502

5. Conclusion

This study uses the non-radial Super SBM model and Malmquist Luenberger index decomposition method to explore the synergistic efficiency of pollution reduction and carbon reduction in the Yangtze River Economic Belt from 2013 to 2022. Constructing a government enterprise public multi-party governance framework, using panel Tobit and other models for empirical analysis, the conclusions are as follows:

Temporal evolution: Collaborative efficiency shows a three-stage change driven by policies. From 2013 to 2016, there was a decline (average annual rate -1.87%), but after 2016, there was a growth (average annual rate +3.15% from 2017 to 2020). After the "dual carbon" target was proposed, the growth rate accelerated (average annual rate +5.43% from 2021 to 2022), and the improvement of technical efficiency contributed significantly to the ML index (68.7%).

Spatial differentiation: Downstream efficiency leads (average 0.872), benefiting from industrial structure and green technology advantages; The resilience of the midstream has recovered, with an average annual growth rate of 1.4% under the epidemic; Upstream catch-up development (with an average annual growth rate of 6.2%), but there is still a gap in technological efficiency compared to downstream.

Driving mechanism: The interaction effect of multi-party governance is significant. The government's green support promotes enterprise transformation, but the transformation has a J-shaped curve characteristic, with a rebound in carbon emissions during the equipment renewal period. The efficiency of public participation has dissipated, and the increase in environmental demands has not effectively transformed into an increase in emission reduction intensity.

Spatial effect: positive spillover of collaborative efficiency ($\rho = 0.213$, $p < 0.05$), and geographic attenuation of technology diffusion. At the same time, there is a phenomenon of "bottom-up competition" in environmental regulation.

This study extends the theory by constructing a multi-agent governance framework and revealing the policy interaction effects; Identify the characteristics of the green transformation stage; Quantify spatial overflow boundaries. The policy recommendation is to establish a governance system of "differential adaptation dynamic optimization spatial collaboration" and implement policies in different regions; Building a collaborative network and utilizing digital technology to enhance public participation efficiency.

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