Research on Performance Measurement and Optimization of Cross-Regional Air Pollution Cooperative Management System

Abstract

Based on defining the concept of cross-regional air pollution collaborative governance performance, a multi-level framework for cross-regional air pollution collaborative governance was constructed. Through measuring the collaborative governance input and output among various regions, the collaborative relationship among different governance entities was assessed. The Super Efficiency SBM-ML Index and Tobit model were used to measure the collaborative governance performance of the Yangtze River Delta and Beijing-Tianjin-Hebei regions from 2016 to 2022. Kernel density estimation and spatial economics theory were then utilized to analyze the results comprehensively.The study found that: The performance of air pollution collaborative governance among different regions in the Yangtze River Delta shows a diverse pattern, with higher performance between Jiangsu, Zhejiang, and Shanghai, which is superior to the performance between these three and Anhui; In the Beijing-Tianjin-Hebei region, air pollution collaborative governance performance displays a more extreme distribution, with high levels of performance between Beijing-Tianjin and Beijing-Hebei, while the performance between Tianjin-Hebei is relatively low; Compared to the Beijing-Tianjin-Hebei region, the Yangtze River Delta's air pollution collaborative governance performance is more significant; Economic development levels and regional coordination have a significant positive effect on cross-regional air pollution collaborative governance performance.Finally, recommendations for optimizing the performance of cross-regional air pollution collaborative governance are proposed.

*Keywords:*Air pollution;Beijing-Tianjin-Hebei; Cross-regional;Synergistic manage

ment performance; Yangtze River Delta

1. Introduction

Air pollution is characterized by high mobility, easy diffusion, and cross-boundary nature(Yang et al., 2022), which makes unilateral governance strategies ineffective in addressing air pollution issues. The spatial spillover effect of air pollution exacerbates the complexity of managing environmental pollution(Sun and Xu, 2023; Xu et al., 2024), and fragmented governance results in low air pollution control efficiency across regions.In response to air pollution, the government has successively introduced policies such as the "Air Pollution Prevention and Control Action Plan" and the "Three-Year Action Plan to Win the Battle for Blue Skies," proposing the deepening of multi-pollutant coordinated control and strengthening of joint air pollution prevention and control across regions(Ma et al., 2019; Sun and Zhou, 2022) .Therefore, only by enhancing interregional communication and cooperation, establishing an air pollution coordinated governance system, and implementing cross-regional air pollution collaborative governance, can positive externalities in environmental governance be achieved, leading to an "1+1>2" effect in environmental outcomes.The essence of collaborative air pollution governance lies in the collective maintenance and management of public environmental resources, a process that depends on close cooperation and high coordination among different regions.However, as the scale of collective participation in air pollution collaborative governance expands, it may lead to significantly higher transaction costs and the emergence of "free-riding" behavior. These adverse factors may ultimately trigger the so-called "collective action dilemma" (Liu and Lei, 2018), thereby reducing the efficiency of air pollution collaborative governance.Clarifying the performance of the air pollution collaborative governance system not only reflects the achievements of collaborative governance in different regions but also serves as a basis for addressing the negative behaviors arising from "collective action."Therefore, a thorough analysis of the current performance, challenges, and key influencing factors of cross-regional air pollution collaborative governance in these areas is crucial for accurately assessing the overall situation of China's regional air pollution governance. This analysis will clarify the bottlenecks faced during collaboration and provide important insights for fully promoting the implementation of cross-regional air pollution collaborative governance strategies, ensuring that governance efforts are targeted, precise, and effective.

Collaborative governance of air pollution has become one of the key research hotspots in the environmental field. Some scholars have conducted research from the perspective of multi-stakeholder collaborative governance.(He and Quan, 2024) analyzed the strategic interactions of local governments in environmental governance and suggested that building a strong "joint prevention and cross-regional governance" alliance is key to overcoming the lack of synergy in environmental governance.(LI, 2020) proposed that the key to overcoming the bottleneck of insufficient collaboration among multiple stakeholders lies in constructing a collaborative governance organization that balances the power and responsibilities of all parties, thereby enabling the allocation and transfer of pollution control resources.(Zhang et al., 2023) studied cross-regional cooperation between governments in managing air pollution, taking into account how internal factors influence the payoffs of the collaboration. The study highlighted that regional development and willingness to cooperate affect the effectiveness of the cooperation, and recommended involving higher-level governments and the public.Other scholars have also studied cross-regional collaborative governance. (Su et al., 2023) examined pollution and carbon reduction collaborative governance in the urban agglomerations of the Yellow River Basin, finding a spatial pattern of "high in the west, low in the east," with internal disparities gradually decreasing over time.(L. Wang et al., 2018) investigated the challenges of air pollution control in the Beijing-Tianjin-Hebei (BTH) region, pointing out that conflicts of interest and administrative barriers in regional cooperation increase the difficulty of air pollution control.(Li and Wang, 2023) based on the perspective of the dynamic effects of joint prevention and control, assessed the policy effects of joint air pollution prevention and control in the Beijing-Tianjin-Hebei region and its surrounding areas. The results indicated that the pollution control effects of regional joint prevention and control have long-term efficacy, with a trend of annual growth.Some scholars have also conducted research on the effectiveness of collaborative governance. (Lv et al., 2022) developed an air pollution control performance evaluation index system based on the Pressure-State-Response (PSR) model, and conducted an empirical evaluation of air pollution control performance in 11 prefecture-level cities in Jiangxi Province.(Matsumoto et al., 2020) used Data Envelopment Analysis (DEA) and the global Malmquist-Luenberger index to evaluate environmental performance based on cross-sectional and time-series data from 27 EU countries.(Tian and Qu, 2022) using recent panel data from 41 cities in the Yangtze River Delta region, constructed a DPSIR multidimensional evaluation index system and applied Principal Component Analysis (PCA) to assess the effectiveness of air pollution control in the Yangtze River Delta region.

A review of the above literature reveals that while there has been substantial research on cross-regional air pollution collaborative governance, discussions on the performance of cross-regional governance have not been sufficiently in-depth. The issue lies in treating each region as an isolated entity, with research limited to internal governance within single regions(Cao et al., 2023; Meng et al., 2021; Sun et al., 2023; Xie and Wang, 2021), thus failing to develop a comprehensive and systematic framework for evaluating cross-regional collaborative governance performance.Regarding the stakeholders involved in air pollution collaborative governance, local governments, bearing the significant responsibility of safeguarding the overall interests within their jurisdiction, face challenges within the current diversified performance evaluation framework, which centers on economic development. These challenges include the "tragedy of the commons," "free-rider" behavior, collective action problems, and the ambiguity of performance evaluation.These issues form real obstacles and "bottlenecks" to establishing a cross-regional collaborative governance framework. Building a systematic and scientific performance evaluation framework and exploring feasible paths to enhance cohesion and centripetal force in cross-regional collaborative gover nance is the key direction for deepening and advancing this process at present. To this end, this paper constructs a complex cross-regional air pollution collabo rative governance system, measuring the inputs and outputs of governance coop eration between regions to evaluate the performance of cross-regional air polluti on collaborative governance. The results are then used to identify and verify th e key factors influencing collaborative governance performance.Finally, a series of targeted optimization recommendations are proposed.

2.Research Foundation

2.1 Cross-Regional Coordinated Air Pollution Management System

Some scholars, based on the input-output perspective(Chen and Zhang, 2021; Xie and Li, 2023), have examined the performance of coordinated air pollution management among governance entities such as governments and enterprises over a certain period, leading to the erroneous performance concepts of "environmental determinism" and "GDP determinism"(Xie and Wang, 2022).However, the essence of coordinated governance is the transition of the behaviors of various governance entities from disorder to order(Si and Wang, 2022).Through mutual consultation and cooperation among multiple entities, the orderly operation and strategic structure of the ecological subsystem are adjusted, resulting in a synergistic effect where the whole ecosystem achieves "1+1>2".Based on this, this study believes that the performance of coordinated air pollution management is mainly reflected in two aspects: collaborative input and collaborative output. Collaborative input includes key elements such as capital investment and equipment allocation, which some scholars have represented with indicators such as investment scale(Pei, 2023). Collaborative output represents the achievements of various participants in the coordinated governance process, which some scholars have represented with indicators such as the degree of environmental improvement(Zheng, 2021).

As shown in Fig. 1, in regions A and B, there are governance entities such as governments, society, and enterprises.The primary aspect of coordinated air pollution management lies in the close cooperation between the government, society, and enterprises.On one hand, society and enterprises, as important participants, effectively supplement the government's efforts, creating a positive interaction system with the government to jointly address the challenges of air pollution management.On the other hand, intergovernmental coordinated governance is equally crucial. By establishing an operating mechanism where "competition" and "collaboration" coexist, it helps to enhance the synergistic benefits between regional systems, fostering a good relationship of both competition and cooperation in pollution management among different regions(Xue et al., 2023) Cross-regional coordinated air pollution management needs to address issues such as breaking through regional barriers and the degree of coordination within the governance system, which requires an accurate measurement of the performance of cross-regional coordinated air pollution management.

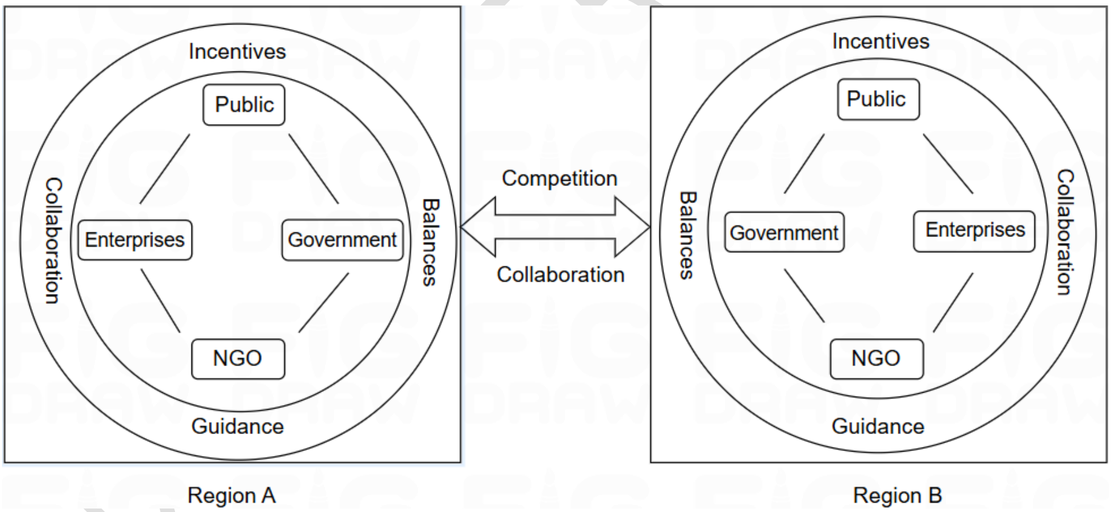


Fig. 1. Cross-Regional Coordinated Air Pollution Management System

The core of measuring cross-regional air pollution collaborative governance performance lies in accurately evaluating the efficiency between collaborative inputs and outputs among regions, thereby reflecting the actual effectiveness of the governance efforts.To this end, this paper constructs a comprehensive cross-regional air pollution governance system framework, drawing on methods from previous research as the theoretical foundation to quantitatively assess the degree of collaboration among regional subsystems.By transforming these collaborative relationships into measurable indicators of collaborative inputs and outputs, it overcomes the challenges of data collection and integration between regions, addressing data gaps.This approach not only establishes a solid foundation for subsequent performance evaluations but also ensures the objectivity, accuracy, and scientific rigor of the evaluation process and results, thereby providing strong support for the continuous optimization of cross-regional air pollution collaborative governance.

2.1 Cross-Regional Coordinated Governance Composite System

2.1.1 Construction of the Composite System and Selection of Order Parameters

The cross-regional air pollution cooperative governance composite system constructed in this paper is a complex structure composed of multiple regional subsystems that are tightly interwoven, influencing and interacting with each other, denoted as $S = \{S_1, S_2, S_3, \cdots S_n\}$.This system can be regarded as being composed of these regional subsystems $S_j (j \in [1, n])$, and any subsystem, in its development process, is influenced by a set of key parameters—namely the order parameters e_{ji}=(e_{j1}, e_{j2}, …e_{jm})(m>1).Due to the complexity of cooperative governance performance measurement, the evaluation index system must be approached from a global and systemic perspective. In this paper, the "Green Development Index System" and the "Ecological Civilization Construction Assessment Target System," developed by the National Development and Reform Commission and the Ministry of Environmental Protection, are used as authoritative bases for measuring the performance of cross-regional air pollution cooperative governance, as detailed in Table 1.

Table 1. Air Pollution Management Subsystems

Subsystem	*Order Parameter*	*Unit*
Resource Input	Proportion of Industrial Pollution Control Investment to GDP	%
	Number of Air Pollution Control Equipment	Sets
	Proportion of Air Pollution Control Expenses to GDP	%
Governance Results	SO2 Emissions	Tons
	NOX Emissions	Tons
Environmental Quality	Days with Air Quality Better than Level II	Days

2.2.2 Measurement of Orderliness and Coordination

After defining the order parameters, the following formula is used to calculate the degree of order for the order parameters (Eq. 1):

$$\mu_i(e_{ji}) = \begin{cases} \dfrac{e_j - \beta_{ji}}{\alpha_{ji} - \beta_{ji}}, i \in [1, l] \\ \dfrac{\alpha_{ji} - e_{ji}}{\alpha_{ji} - \beta_{ji}}, i \in [l+1, m] \end{cases} \quad (1)$$

Among them, e_{ji}={e_{j1}, e_{j2}, ...e_{jl}} represents the positive indicator and e_{ji}=$e_{j(l+1)}$, $e_{j(l+2)}$, ...e_{jm}} represents the negative indicator; α_{ji}, β_{ji} respectively denote the upper and lower bounds of the order parameter e_{ji}, where 110% of the maximum and minimum values of the order parameter e_{ji} are taken as its upper and lower bounds.The orderliness of the regional air pollution control subsystem is a key indicator for measuring the degree to which the subsystem has transitioned from a disordered to an ordered state.The specific calculation formula is as follows (Eq. 2):

$$\mu(S_j) = \sqrt[m]{\prod_{i=1}^{m} \mu_i(e_{ji})} \quad (2)$$

By evaluating the orderliness of the air pollution control subsystems in each region, the level of coordinated development between different regions can be further calculated.This coordination index reflects the actual effectiveness of the collaborative efforts between regional air pollution control subsystems during a specific time period (from the initial moment t0 to the development stage t1), serving as a dynamic measurement standard that evolves continuously over time.Specifically, let the orderliness of the regional air pollution control subsystem at the initial stage t0 $\mu^0(S_j)$, and at the subsequent development stage t1, the orderliness becomes $\mu^1(S_j)$. Based on the change in orderliness, we define the coordination degree C of the cross-regional composite system, and its calculation formula is as follows (Eq. 3):

$$C = \theta \times \sqrt[n]{\left| \prod_{j=1}^{n} \left[\mu^1(S_j) - \mu^0(S_j)\right] \right|} \tag{3}$$

$$\theta = \frac{min[\mu^1(S_j) - \mu^0(S_j)]}{|min[\mu^1(S_j) - \mu^0(S_j)]|}, \quad \mu^1(S_j) - \mu^0(S_j) \neq 0 。$$

2.3 Measurement of Coordinated Inputs and Outputs

The coordination degree between regions, as a key indicator for evaluating the closeness of collaborative relationships between different regions, is fundamentally reflected in two objective aspects: collaborative input and collaborative output.To quantify this coordination effect, it is necessary to comprehensively consider the actual inputs and outputs of each region in air pollution control, and combine this with the level of interregional coordination to precisely calculate the collaborative input and output between regions.The calculation formula is as follows (Eq. 4-5):

$$CI = (IT_A + IT_B) \times C_{AB} \tag{4}$$

$$CO = (0T_A + 0T_B) \times C_{AB} \tag{5}$$

Among them, CI and CO represent the coordinated inputs and outputs of region AB, respectively. IT_A and IT_B represent the governance inputs of regions A and B, respectively, and OT_A and OT_B represent the governance outputs of regions A and B, respectively. C_{AB} represents the coordination degree between regions A and B.

3.Measurement of Cross-Regional Coordinated Air Pollution Management Performance

3.1 Sample Selection and Data Collection

The Central Committee of the Communist Party of China and the State Council formulated the "Action Plan for Continuous Improvement of Air Quality," highlighting key areas centered on Beijing-Tianjin-Hebei, the Yangtze River Delta, and the Pearl River Delta. The plan aims to promote high-quality economic development through continuous air quality improvement(Wang J. et al., 2018). Based on this, this paper selects the Beijing-Tianjin-Hebei and Yangtze River Delta regions as the research subjects, with Beijing, Tianjin, and Hebei chosen for the Beijing-Tianjin-Hebei region, and Shanghai, Jiangsu, Zhejiang, and Anhui chosen for the Yangtze River Delta region.The study period is from 2016 to 2022, with 2015 data selected as the base period to calculate the coordination degree between the two regions from 2016 to 2022.Statistical data is sourced from the "China Statistical Yearbook," "China Environmental Statistical Yearbook," and "China Energy Statistical Yearbook." Missing data were supplemented using interpolation methods.

3.2 Super-Efficiency SBM Model

Data Envelopment Analysis (DEA) is the most common model for efficiency evaluation. In cases of multiple inputs and outputs, it may result in excess input factors and insufficient output, leading to input factor "congestion or slack"(Hou and Yao, 2018). The Super-Efficiency SBM model combines the advantages of the

Super-Efficiency DEA and SBM models, taking into account variable slack and undesirable outputs. This allows for further comparison and ranking of decision-making units with an efficiency score of 1, providing a more objective measurement of air pollution management efficiency. The model is as follows (Eq. 6):

$$
\begin{aligned}
min\rho &= \frac{1+\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1-\frac{1}{S_1+S_2}\left(\sum_{r=1}^{s_1}\frac{s_r^+}{y_{rk}}+\sum_{t=1}^{s_2}\frac{s_t^{b-}}{y_{tk}^b}\right)} \\
s.t.\quad & \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leqslant x_{ik} \\
& \sum_{j=1,j\neq k}^{n} y_{rj}\lambda_j - s_r^+ \leqslant y_{rk} \\
& \sum_{j=1,j\neq k}^{n} y_{ij}^b\lambda_j - s_t^{b-} \leqslant y_{ik}^b \\
& 1-\frac{1}{S_1+S_2}\left(\sum_{r=1}^{q_1}\frac{s_r^+}{y_{rk}}+\sum_{t=1}^{q_2}\frac{s_t^{b-}}{y_{tk}^b}\right) > 0 \\
& \lambda, s^+, s^- \geqslant 0
\end{aligned}
\tag{6}
$$

Suppose there are n decision-making units, each with varying efficiencies in air pollution collaborative governance.Each decision-making unit consists of m inputs, S_1 expected outputs, and S_2 undesired outputs; ,s_i^-、s_r^+ and s_t^{b-} represent the slack variables for inputs, expected outputs, and undesired outputs, respectively.The variables x_{ik}、y_{rk}、y_{tk}^b represent the i-th input, i expected output, and r undesired output of the t decision-making unit, respectively.

The use of the super-efficiency SBM model requires the selection of input and output variables. This paper constructs the performance measurement indicators for air pollution management as shown in Table 2. These are converted into collaborative input and output variables using Formulas (4) and (5), and then incorporated into Model (6) for calculation.

Table 2. Performance Measurement Indicators System for Air Pollution Management

Type	***Indicator Name***	***Unit***
Input	Industrial Pollution Control Investment	Ten Thousand Yuan
	Number of Exhaust Pollution Control Devices	Units
	Exhaust Pollution Control Costs	Ten Thousand Yuan
Desired Output	GRP	Hundred Million Yuan
Undesirable Output	Industrial SO2 Emissions	Tons
	Industrial NOX Emissions	Tons

3.3 Malmquist Luenberger Index

The super-efficiency SBM method can only be used to evaluate the static relative efficiency of the research object and cannot reflect its dynamic efficiency changes.The Malmquist Luenberger index can not only measure total factor productivity, technical efficiency, and technological progress over multiple sample periods,but it also extends its analytical capabilities further to capture the dynamic changes of these efficiency values over time,specifically, the trends and magnitudes of increases and decreases in efficiency values.It represents the change in productivity of the decision-making unit from period t to t+1.This compensates for the limitation of the super-efficiency SBM method, which can only reflect static efficiency evaluations.The formula is as follows (Eq. 7):

$$ML\_GTFP_t^{t+1} = \left[\frac{\left(1 + \overrightarrow{D_0^t}(x^t, y^t, b^t; y^t, -b^t)\right)}{\left(1 + \overrightarrow{D_0^t}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})\right)} * \frac{\left(1 + \overrightarrow{D_0^{t+1}}(x^t, y^t, b^t; y^t, -b^t)\right)}{\left(1 + \overrightarrow{D_0^{t+1}}(x^{t+1}, y^{t+1}, b^{t+1}; y^{t+1}, -b^{t+1})\right)} \right.$$

$$= EC \times TC$$

When the Malmquist Luenberger Index is greater than 1, it indicates an improvement in air pollution control efficiency in the region from period t to t+1; otherwise, it indicates a decline.The total factor productivity index can be decomposed into the technical efficiency index and the technical progress index, thereby allowing for a deeper exploration of the underlying causes of air pollution control in various regions.

3.4 Empirical Analysis

3.4.1 Static Analysis Results

Using MAXDEA 7 Ultra software and the super-efficiency SBM model based on undesirable outputs, the efficiency values for cross-regional air pollution management in the Beijing-Tianjin-Hebei and Yangtze River Delta regions from 2016 to 2022 were calculated. The results are shown in Fig. 2.

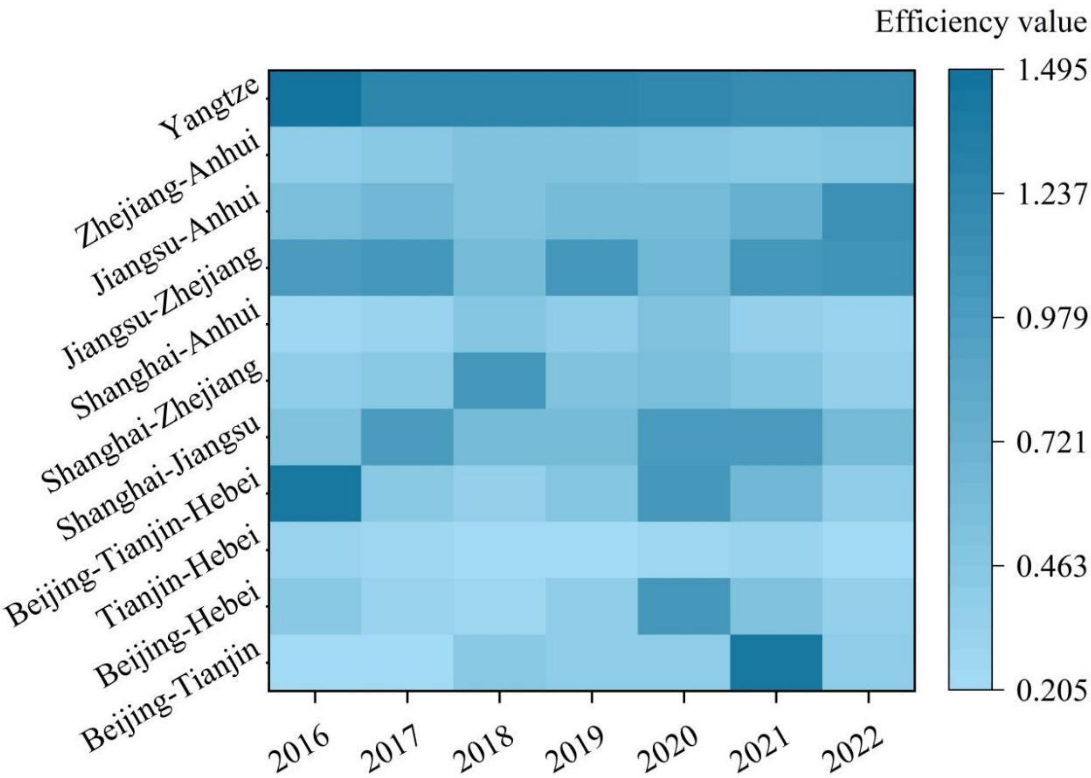


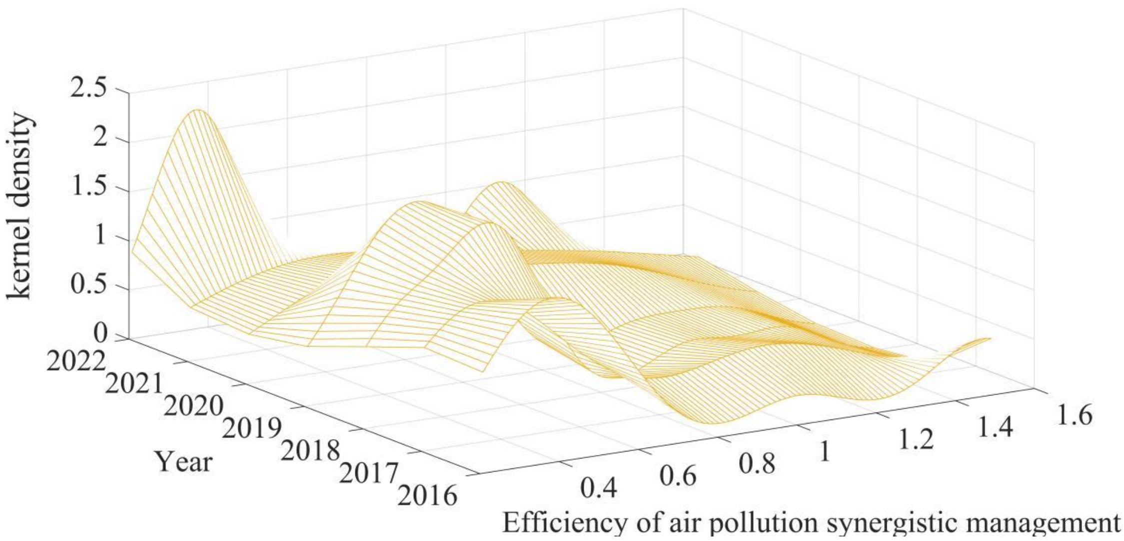
Fig. 2. Efficiency Values of Air Pollution Coordinated Management in Various Regions

From the overall distribution trend, Fig. 2 shows that the efficiency of air pollution coordinated management in the Yangtze River Delta and Beijing-Tianjin-Hebei regions increased from 2016 to 2022. However, the level of coordinated management remains relatively low. Most regions have coordinated management efficiency levels concentrated in the range of 0.4 to 0.8, with a few regions achieving efficiency values of 1.0 or higher. This indicates a significant disparity in air pollution coordinated management levels among the regions. The two regions with the highest efficiency levels in air pollution coordinated management are the Yangtze River Delta and Jiangsu-Zhejiang. Specifically, the average efficiency of the Yangtze River Delta region reaches 1.26, while there is a substantial gap in efficiency levels within the Beijing-Tianjin-Hebei region, with the efficiency in the Tianjin-Hebei area being below 0.3, indicating considerable room for improvement in air pollution coordinated management in that region.

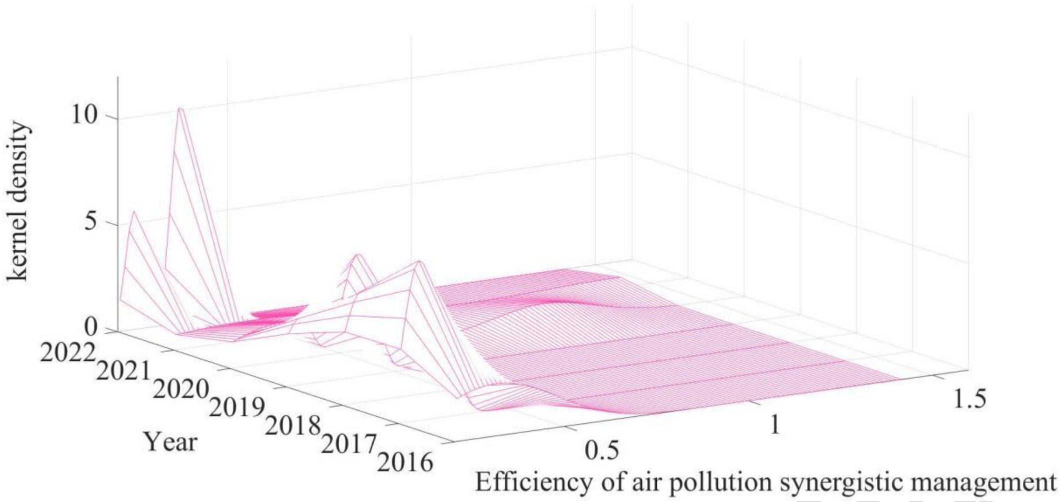
Although the collaborative governance efficiency in the Beijing-Tianjin-Hebei and Yangtze River Delta regions shows an overall upward trend, it is also accompanied by periods of fluctuation.Due to the "12th Five-Year Plan for Key Urban Air Pollution Prevention and Control" and the "Air Pollution Prevention and Control Action Plan," which propose the establishment of a "joint prevention and control mechanism for air pollution" and target control of pollutant emissions for the Beijing-Tianjin-Hebei and Yangtze River Delta city clusters(He et al., 2019), the collaborative governance is still in its early stages. Therefore, in the short term, the constraints on economic growth outweigh the improvements in air quality, leading to a temporary decline in air quality efficiency.

The efficiency of air pollution collaborative governance in the Yangtze River Delta region is higher than that in the Beijing-Tianjin-Hebei region.This advantage is primarily attributed to the pioneering practices in environmental collaborative governance in the Yangtze River Delta region. As early as 2014, the Yangtze River Delta established a strategy for environmental collaborative governance(Li et al., 2023), laying a solid foundation for its subsequent in-depth development.With the approval of the "Overall Plan for the Ecological and Green Integrated Development Demonstration Zone in the Yangtze River Delta," the integrated development of the Yangtze River Delta has entered the full implementation stage.As an economically developed region, the Yangtze River Delta has invested substantial resources in collaborative governance, significantly enhancing overall environmental benefits.These investments not only improved governance effectiveness but also further promoted the sustainable development of the Yangtze River Delta region(Ma et al., 2018).

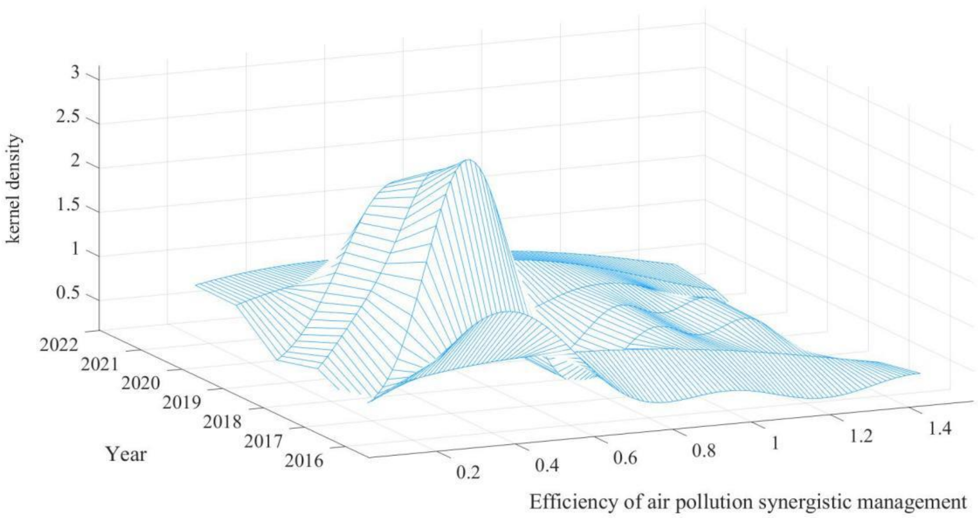
To further investigate the temporal characteristics of cross-regional coordinated air pollution management efficiency, kernel density estimation with a Gaussian normal distribution non-parametric kernel function was applied to the observation points from 2016 to 2022(Megheib, 2023). The resulting kernel density distributions at each time point are shown in Fig. 3.



(a) Overall



(b) Beijing-Tianjin-Hebei



（c）Yangtze River Delta

Fig. 3. Three-Dimensional Kernel Density of Air Pollution Coordinated Management Efficiency

Analysis of Fig. 3(a) reveals that:□ The kernel density curves for the Yangtze River Delta and Beijing-Tianjin-Hebei regions show an overall rightward shift, indicating that the level of air pollution collaborative governance in these regions is continuously improving.□ During the observation period, there are side peaks, and the overall distribution of the peaks shows a "one large, one small" pattern. The "large peak" is primarily concentrated in areas with lower levels of air pollution collaborative governance, while the "small peak" is located in regions with higher efficiency values, indicating a two-tier differentiation and spatial imbalance in air pollution collaborative governance.□ The width of the peaks continues to narrow, and their height exhibits a "high-low-high" pattern, indicating that the disparity in air pollution collaborative governance among regions is gradually narrowing.According to the Environmental Kuznets Curve theory, there is a special inverted "U" relationship between environmental pollution and economic development.Specifically, as the economy initially grows, the reliance on extensive economic growth models increases pressure on the environment and ecosystem, leading to intensified ecological damage. During this stage, there is a positive correlation between economic development levels and the extent of ecological damage.However, when the regional economy advances to a higher development stage, the optimization of the industrial structure and the shift of economic development focus towards technology-intensive industries lead to gradual improvements in environmental quality with economic growth. During this stage, the level of economic development shows an inverse correlation with the degree of environmental degradation.

According to Fig. 3(b):□ The distribution of air pollution collaborative governance efficiency in the Beijing-Tianjin-Hebei region has shifted overall to the right, indicating that its efficiency is gradually improving.□ In the later period, the Beijing-Tianjin-Hebei region has developed a significant side peak, indicating a notable two-tier differentiation within the region.□ The right side of the kernel density plot shows a long tail, indicating that the air pollution collaborative governance efficiency in this region is relatively low.

According to Fig. 3(c):□ The distribution of air pollution collaborative governance efficiency in the Yangtze River Delta region has shifted overall to the right, indicating that its efficiency is continually improving.□ From 2018 to 2020, the height of the main peak has shown an increasing trend, indicating that the overall disparity in air pollution collaborative governance levels among regions is narrowing.□ The transition of the kernel density plot from "bimodal" to "unimodal" indicates that the polarization phenomenon in the region is gradually disappearing.

3.4.2 Results of Dynamic Analysis

Based on static analysis, the dynamic changes in air pollution coordinated governance efficiency are explored using the Malmquist Luenberger index. The average values of the Malmquist Luenberger index for the efficiency of coordinated governance between regions in the two areas are compared and analyzed, as shown in Fig. 4.

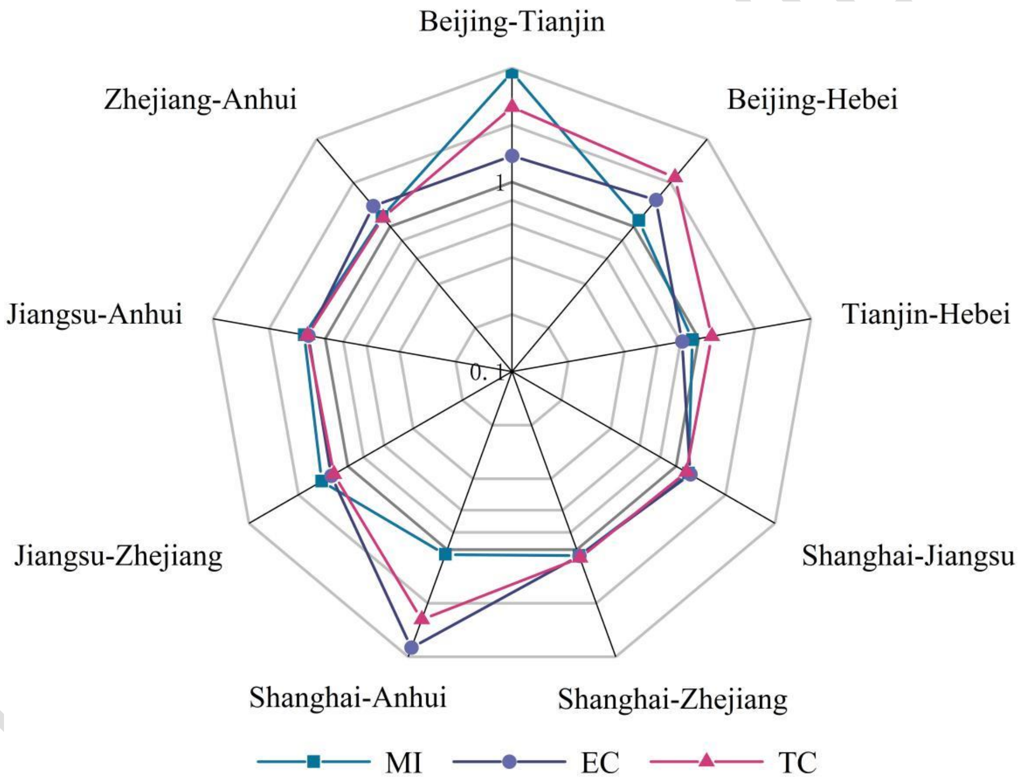


Fig. 4. Schematic Diagram of Coordinated Governance Efficiency in Beijing-Tianjin-Hebei and the Yangtze River Delta

As shown in Fig. 4, the technology advancement index is generally high, with the Beijing-Tianjin and Shanghai-Anhui regions being particularly notable. This trend is likely attributable to the resource advantages of Beijing and Shanghai, such as their robust economic development and high levels of technological innovation, which have driven a rapid increase in the technology advancement index for these regions. Conversely, the technology efficiency index in the Tianjin-Hebei region is lower compared to other coordinated regions. This may be due to the region's economic underdevelopment and its industrial structure, which is heavily oriented towards high-pollution and energy-intensive industries. These factors contribute to insufficient investment in technological research, innovation, and application, thus inhibiting improvements in technology efficiency levels.

The performance levels of cross-regional air pollution management in the Yangtze River Delta region display a diversified distribution. Based on a comprehensive assessment of the total factor productivity (TFP) of each region, the regions can be categorized into three tiers. The Jiangsu-Zhejiang and Jiangsu-Anhui regions, with their outstanding performance, belong to the top tier, followed by the Shanghai-Jiangsu and Zhejiang-Anhui regions in the second tier, while Shanghai-Zhejiang and Shanghai-Anhui form the third tier. Two observations emerge from the analysis: First, the TFP of cross-regional management within the Jiangsu-Zhejiang-Shanghai (JZS) area is higher than that of the Jiangsu-Zhejiang-Shanghai-Anhui (JZSA) region. From a spatial economics perspective, Anhui, as a relatively underdeveloped region, has a primary and secondary industry concentration that limits its ability to effectively address economic development and environmental pollution issues, resulting in poorer air pollution management outcomes. In contrast, the Jiangsu-Zhejiang-Shanghai region, as a more economically developed area, has benefited from economic growth that promotes the optimization and upgrading of its industrial structure. This region is gradually shifting from high-energy, high-pollution, energy-intensive industries (e.g., coal and chemical industries) to service sectors and other tertiary industries(Ren et al., 2024) This industrial transition directly leads to reduced air pollution emissions, significantly enhancing the effectiveness of air pollution management. Second, the TFP of cross-regional management in Jiangsu-Anhui and Zhejiang-Anhui is higher than that in Shanghai-Anhui. Geographical proximity affects the efficiency of cross-regional management; Jiangsu-Anhui and Zhejiang-Anhui are directly adjacent, whereas the distance between Shanghai and Anhui is too large, resulting in lower management effectiveness compared to Jiangsu-Anhui and Zhejiang-Anhui.

In the Beijing-Tianjin-Hebei region, collaborative governance performance across the areas demonstrates significant disparities.The total factor productivity of collaborative governance between Beijing-Tianjin and Beijing-Hebei has reached relatively high levels, whereas the productivity between Tianjin-Hebei is notably lower.As the central hub of the Beijing-Tianjin-Hebei collaborative development strategy, Beijing has played a significant leadership and driving role in enhancing the efficiency of collaborative governance with Hebei and Tianjin(Li, 2022).However, the poor collaborative governance performance between Tianjin and Hebei may be attributed to several factors: First, a comparative analysis of collaborative inputs and outputs shows that Tianjin-Hebei lags significantly behind Beijing-Tianjin and Beijing-Hebei in overall collaborative efforts, revealing clear shortcomings in scaling and integration.Second, although the gap in total factor productivity between Tianjin-Hebei and Beijing-Hebei is not significant, a deeper examination of the technology progress index reveals that Tianjin-Hebei lags behind Beijing-Hebei in this key metric. This suggests that technological advances in Tianjin-Hebei have not translated into governance efficiency, indicating ample room for improvement in the practical application of scientific achievements.Third, compared to Tianjin, Beijing's advantages in terms of financial and technological resources create a degree of suppression on the collaborative governance efforts between Tianjin and Hebei.

A comparison of the overall collaborative governance efficiency between the Yangtze River Delta and Beijing-Tianjin-Hebei regions is shown in Fig. 5.

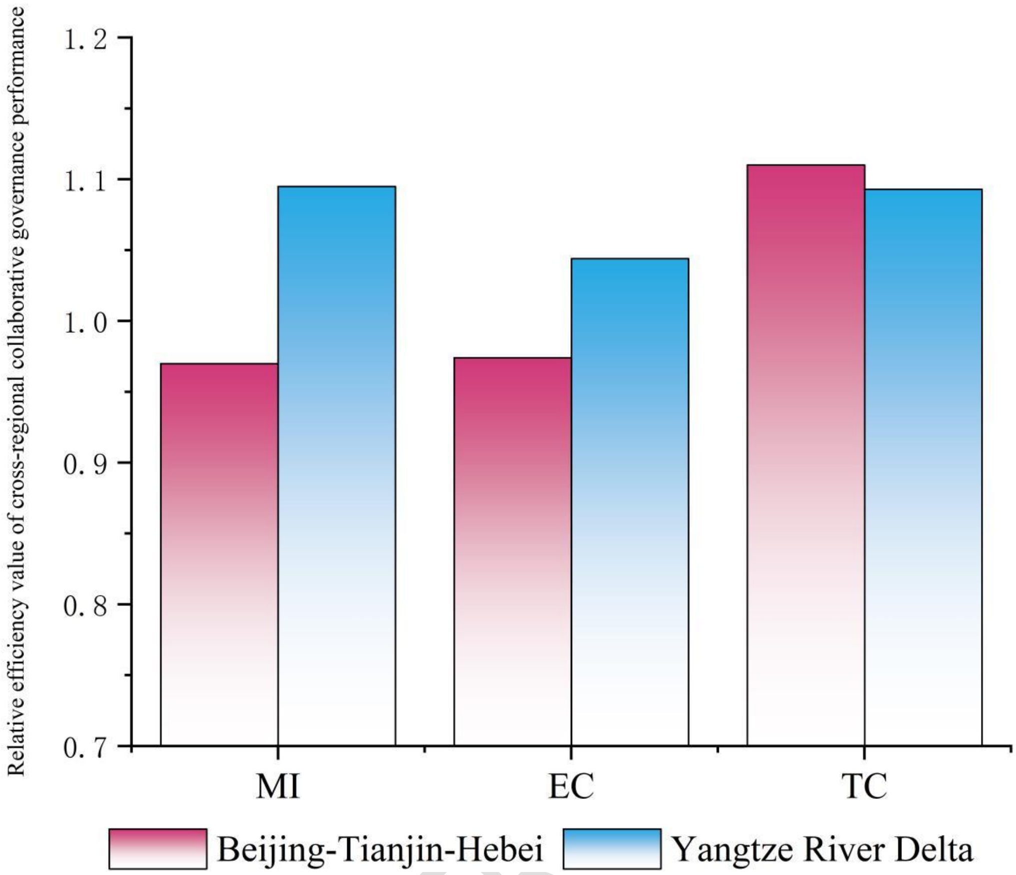


Fig. 5. Comparison of Overall Collaborative Governance Efficiency between Beijing-Tianjin-Hebei and the Yangtze River Delta Regions

Fig. 5 reveals that there is a noticeable gap between total factor productivity (TFP) and technical efficiency, with the differences in TFP being particularly pronounced. However, it is worth noting that the Beijing-Tianjin-Hebei region has achieved significant progress in collaborative air pollution management in recent years. Nevertheless, compared to the Yangtze River Delta region, the heterogeneity in economic development, industrial structure, and technological advancement among cities in the Beijing-Tianjin-Hebei region has led to a relatively late start in collaborative air pollution management. Additionally, there is a notable imbalance in collaborative governance within the region, which requires further efforts to optimize and enhance the management practices.

4.Analysis of Factors Affecting Cross-Regional Collaborative Governance

Performance

4.1Identification of Influencing Factors

By analyzing the results of cross-regional air pollution collaborative governance performance measurement, we found that:

The total factor productivity in the Yangtze River Delta region is higher than that in the Beijing-Tianjin-Hebei region, which may be influenced by the economic development level of the regions.On one hand, rapid economic development increases investment in environmental governance; on the other hand, higher economic levels lead to increased public demand for environmental quality.Based on this, the following hypothesis is proposed:

H1: The level of economic development is positively correlated with cross-regional air pollution collaborative governance performance.

The total factor productivity of collaborative governance among Jiangsu, Zhejiang, and Shanghai is higher than that of the collaboration between Jiangsu, Zhejiang, Shanghai, and Anhui.This phenomenon can be attributed to two reasons: First, the higher economic development level in Jiangsu, Zhejiang, and Shanghai has led to an optimized industrial structure, which reduces pollutant emissions and consequently improves air quality efficiency(Wang et al., 2022). Second, the application of advanced technologies in industrial production significantly enhances technological and process levels, thereby indirectly promoting improvements in air quality efficiency.Based on this, the following hypothesis is proposed:

H2: The industrial structure is positively correlated with cross-regional air pollution collaborative governance performance.

In the cross-regional collaborative governance within the Beijing-Tianjin-Hebei (Jing-Jin-Ji) region, the collaboration between Tianjin and Hebei has notably become a weak link. This shortcoming may arise from insufficient scale and depth of cooperation between Tianjin and Hebei, as well as the inhibitory effect of Beijing's resource advantages(Hu, 2024). These factors collectively represent the insufficient level of collaboration in the Tianjin-Hebei region. Based on this, the following hypothesis is proposed:

H3: The level of collaboration between regions is positively correlated with the performance of cross-regional air pollution control.

The Tobit model is used to examine the key influencing factors of cross-regional air pollution coordination to verify whether the hypotheses are valid.

4.2Tobit Model

The Tobit model is used to analyze the cross-regional collaborative governance performance and key influencing factors in the Yangtze River Delta and Beijing-Tianjin-Hebei regions. The model can be expressed as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \varepsilon \tag{8}$$

In the model, Y represents the collaborative governance performance between regions, expressed as total factor productivity; X_1 represents the economic development level between regions, expressed as the logarithm of per capita GDP; X_2 represents the industrial structure, expressed as the proportion of the secondary industry, i.e., industrial added value, to GDP in different regions; X_3 represents the degree of regional collaboration; β_0 is the constant term, and β_1、β_2、β_3 are the coefficients for the respective independent variables; ε represents the error term, and $\varepsilon \sim (0, \sigma^2)$.

4.3Regression Results Analysis

The model was run using Stata 17.0 software, and the following results were obtained.

Table 3. Tobit Model Regression Results

Influence Factor Variables	*Coefficient*	*Standard Error*	*T-Statistic*	*Significance Level*
Economic Development Level	0.5294	0.1431	3.70	***
Industrial Structure	1.0545	0.5918	1.78	*
Inter-Regional Coordination Degree	3.0695	1.1458	2.68	***
Constant	-1.1607	0.4376	-2.65	***

Note: *, **, and * represent significance levels of 1%, 5%, and 10%, respectively.**

Table 3 shows that economic development level, industrial structure, and inter-regional synergy are significantly positively correlated with cross-regional air pollution collaborative governance performance. Among these factors, the economic development level and inter-regional synergy have the most significant impact on collaborative governance performance. Inter-regional synergy reflects the degree of closeness in collaborative connections between different regions; the tighter the connections, the better the collaborative governance effect. Another significant factor affecting cross-regional governance performance is economic development level. On one hand, this is mainly due to improvements in production processes, increased resource utilization efficiency, and advancements in environmental governance technology, which drive economic growth toward cleaner and more intensive models. On the other hand, as people pursue higher-quality lives, awareness of environmental protection continues to increase. Only when GDP reaches a certain scale can scale effects be effectively realized. With GDP growth, accumulated factor endowments will create competitive advantages, driving regions to achieve faster development, creating an "acceleration" effect(Li and Qu, 2024), exchanging lower environmental costs for higher economic returns. The industrial structure also impacts air pollution collaborative governance performance. Industrial pollution, such as sulfur dioxide and respirable particulate matter, is a major source of air pollution, primarily resulting from combustion and transportation activities in industrial production processes. Industrial enterprises can improve air environment governance efficiency by upgrading production processes, renewing equipment, and optimizing management models. Therefore, ongoing adjustments to industrial structure are crucial for enhancing environmental efficiency.

5. Conclusions and Recommendations

5.1Conclusions

This paper focuses on the performance of cross-regional air pollution collaborative governance. Based on a composite system of cross-regional collaborative governance, it measures the performance levels of cross-regional air pollution collaborative governance in the Beijing-Tianjin-Hebei and Yangtze River Delta regions using collaborative inputs and outputs. Additionally, it empirically analyzes the influencing factors of cross-regional collaborative governance. The research conclusions are as follows:

The performance levels of cross-regional collaborative governance in the Beijing-Tianjin-Hebei region show an extreme distribution. The collaborative governance performance between Beijing-Hebei and Beijing-Tianjin reaches a relatively high level, while the performance level between Tianjin-Hebei is significantly lower than that between Beijing-Hebei, indicating a clear disparity.

Within the Yangtze River Delta, the performance levels of collaborative governance among different regions exhibit a tiered and diversified distribution. The collaborative governance performance between Jiangsu, Zhejiang, and Shanghai is higher than their respective performance with Anhui. This disparity partially reflects the impact of economic development levels and geographical proximity on collaborative governance performance, where regions with similar economic development levels and closer geographical proximity tend to have higher collaborative governance performance.

Through the analysis of the factors affecting cross-regional air pollution collaborative governance performance, we find that economic development level and inter-regional collaboration have the greatest impact on cross-regional air pollution governance performance. Higher economic development levels lead to increased resource investment and technical support for air pollution control in cities and regions, thereby enhancing collaborative governance outcomes. Higher levels of inter-regional collaboration result in closer cooperation in policy formulation, enforcement, technology sharing, and resource allocation, which not only effectively reduces redundant work and resource waste but also creates a collective effort to address air pollution issues. Additionally, the industrial structure also affects air pollution governance performance. For instance, a higher proportion of high-pollution and high-energy-consumption industries increases governance difficulty and negatively impacts governance performance.

5.2Recommendations

First, improve the participation mechanism for multiple stakeholders. On one hand, enhance classroom education, strengthen corporate training, and conduct a variety of extracurricular activities to build a comprehensive and multi-dimensional environmental education system. Integrate energy conservation, green commuting, and other environmental protection measures into everyday life, effectively promoting the adoption and practice of environmental awareness. On the other hand, to achieve the governance vision of "participation by all," a series of initiatives should be implemented to broaden the orderly participation channels for businesses, non-governmental organizations, and the public. These measures should fully guarantee stakeholders' rights to information, oversight, feedback, and litigation, creating an open, inclusive, and co-governed environment.

Second, establish effective collaborative governance organizations. The central government should play a core role by setting up a Regional Coordination Office under the Ministry of Environmental Protection, responsible for formulating policy frameworks, coordinating regional conflicts of interest, and handling pollution disputes effectively. Additionally, encourage local governments to voluntarily form inter-regional coordination committees, including multi-functional groups for policy planning, information communication, and expert consultation, to create a governance network combining vertical guidance with horizontal collaboration, thereby providing solid support for local governments to effectively address air pollution issues.

Third, establish a comprehensive collaborative governance system. A well-developed collaborative governance system is a prerequisite for ensuring that the effects of collaborative governance are fully realized. First, it is necessary to establish a consultation mechanism to conduct in-depth discussions and negotiations on cross-boundary air environmental disputes, enhancing mutual understanding and facilitating the timely identification and preemptive resolution of issues. Second, a scientific and rational institutional framework must be established to provide solid support. This includes coordination and action plans between different levels of government, evaluation standards for joint prevention and control effectiveness, and rules for addressing major environmental issues.

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