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A Study on the Effect of Innovation-Driven Policies on Industrial Pollution Reduction: Evidence from 276 Cities in China

Qingwei Shi [1], Yupeng Hu [1] and Tiecheng Yan [2,*]

[1] Business College, Southwest University, Chongqing 400715, China
[2] College of Civil Engineering, Longdong University, Qingyang 745000, China
* Correspondence: zzr@ncut.edu.cn

Abstract: The societal effects of industrial pollution have spurred heated debates, but more research into the influence and internal mechanism of innovative pilot city policies (IPCPs) on industrial emissions is needed. Using panel data from 276 Chinese cities between 2004 and 2018, the study employs a multi-period difference-in-differences model to explore the effects and mechanisms of pilot policies on industrial SO_2 emissions, with a specific focus on how they can be mitigated by innovative techniques. The results indicate that (1) the Chinese innovative pilot city policies (CIPCPs) significantly reduced emissions in urban areas; (2) the concentration of talent, innovation policy, venture capital, and technology plays a pivotal role; and (3) the SO_2 reduction effects are more pronounced in larger cities, such as super-large, mega-, and first-tier cities in the southeast, and in cities with a high market potential. This study provides empirical evidence to support the promotion of sustainable economic and social development, the resolution of environmental pollution problems, and the enhancement of public health.

Keywords: innovative city pilot policy (IPCP); industrial SO_2 emissions; DID; mediated effect model

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1. Introduction

The excessive reliance on fossil fuel energy has led to serious air pollution problems [1], and one of the most significant components is sulfur dioxide (SO_2). In 2007, China's SO_2 emissions reached 36.6 million tons [2], ranking second globally. Research indicates that it has adverse effects on human health, including the potential to cause lung cancer [3]. The ecological harm it causes is also significant, as excessively heavy emissions cause a rapid increase in soil acidification [4], forest decline [5], and severe harm to crops [6]. More than 500 million city residents in China are exposed to polluted air [7], and many countries have enacted legislation to reduce SO_2 emissions, such as the US Clean Air Act and the European Union's Industrial Emissions Directive, which imposes restrictions on specific industries. In China, the "Eleventh Five-Year Plan" for the Prevention and Control of Acid Rain and Sulfur Dioxide Pollution emphasizes the urgency of controlling SO_2 pollution and achieving an annual average concentration of SO_2 in city air by 2020. These policies underscore the importance of sustainable ecological development. Li et al. (2017) found that China's emissions decreased by 75% from 2005 to 2016, while India's increased by 50% [2]. Given that the industrial sector is China's primary source of SO_2 emissions, it is essential that the factors influencing its reduction be examined. This paper explores the determinants of industrial emission reduction with a specific focus on the severe impacts of SO_2 on the environment and human health.

Scholars have extensively researched the driving force of innovation [8] to provide more effective treatments for acute diseases [9–11]. Others have explored the relationship between innovation and the environment [12], and found that innovation promotes sustainable city development and plays an essential role in controlling pollution [13]. Researchers such as Wang et al. (2019) and Zhang et al. (2018) have shown that technological innovation is critical for environmental protection and has a more significant impact on e-waste than government policy [14,15].

Since Shenzhen was designated a pilot city in 2018, nearly 78 others followed in that year. According to the "National Innovation-Driven City Innovation Capability Evaluation Report 2019," these cities account for 78% of national R&D funding and over 85% of patents. This innovation-driven policy may also have a positive effect on industrial SO_2 emission reduction. To complete the research gap in reducing industrial SO_2 emissions, this paper investigates the effects of China's innovation-driven pilot city policy (CIPCP) by examining the amount of industrial SO_2 emissions.

The contribution of this paper is demonstrated in three main ways. First, we treated CIPCP as a quasi-natural experiment and employed a multiple-timepoint difference-in-differences (DID) model to study its effect, which expanded the scope of CIPCP research. Second, we conducted a multidimensional analysis of the critical factors influencing emissions. We use several testing mechanisms, including PSM-DID and placebo tests, to eliminate the effects of unobserved city-level factors on our conclusions to ensure the reliability of our results. Third, we determined the heterogeneous impact of city size, regional distribution, and market potential on emission reduction. Using a mediation effect model, we analyzed the key driving factors for reduction: talent, innovation policy, risk investment, and technological aggregation. This study provides a comprehensive examination of the impact of the CIPCP on industrial SO_2 emission reduction.

2. Literature Review

Scholars have conducted extensive research into SO_2 emission reduction. Streets and Waldhoff (2000) analyzed China's emissions from 1990 to 1995 and predicted trends that provided insights into early emission control [16]. Li et al. (2022), Sun et al. (2022), and Zhang et al. (2020) studied sulfur-removal technologies and the feasibility of stopping emissions before they are released [17–19]. Shams et al. (2021) applied artificial neural networks (ANN) and multiple linear regression (MLR) models to predict SO_2 concentrations, providing technical support for emission measurements [20]. Kaminski (2003) studied the modernization of existing industrial coal-burning equipment to reduce SO_2 emissions and energy production costs [21]. Improvements in demand structure can also reduce emissions [22], and in this regard, some scholars have examined the effect of government policies; for example, the decrease in atmospheric SO_2 in the Netherlands is related to national and international control measures [23]. In addition, export tax rebates can reduce emissions as part of a new concept for industrial pollution control [24]. Subsidies for desulfurization prices are another means and have better results in less developed areas [25]. However, the literature on whether the CIPCP can reduce industrial SO_2 emissions still needs to be improved. This paper discusses the progress of CIPCP research.

2.1. Effects of CIPCP on Environmental Pollution

Scholars have extensively researched CIPCP since China established its first pilot innovation city in 2018. However, much of the research has focused on its environmental and innovative impacts. Studies have shown that these policies have promoted city ecological efficiency [26], significantly reduced carbon emissions [27], and significantly advanced the benefits of green logistics using a time-varying difference model [28]. Additionally, using the propensity score-matching DID method, Yang et al. (2022) studied the impact of CIPCP on city energy efficiency and found that the policies were significantly beneficial [29]. Similarly, Zhang and Wang (2022) researched how CIPCP affected knowledge innovation (KIE) and knowledge transformation efficiency (KTE) [30] and found a significantly positive effect on both. Furthermore, Li et al. (2022) studied CIPCP for its effect on urban green innovation using DID and found that it was significantly improved [31].

In summary, the existing research has mainly focused on the impact of CIPCPs on the ecological environment and innovation. However, it remains to be seen whether these policies' promotion of ecological efficiency includes a reduction in SO_2 emissions from the industrial sector. There are instances in the literature that support the idea that CIPCPs can reduce SO_2 emissions from the industrial sector. Therefore, based on panel data from 276 Chinese cities between 2004 and 2018, this study employs a multi-timepoint difference-in-differences model to investigate the effect and mechanism of CIPCPs on the reduction of SO_2 emissions from the industrial sector. The results confirm that CIPCPs reduced SO_2 emissions from the industrial sector. We further examine the mediating effects of factors, such as talent concentration, innovation policy concentration, venture capital concentration, and technology concentration, on reducing SO_2 emissions from the industrial sector.

2.2. Mediating Effects

The CIPCP can reduce the emissions of SO_2 from the industrial sector through the concentration of talent. At present, the importance of talent is becoming increasingly significant. Lindburg et al. (2019) analyzed the main development trends that affect skill and found an increasing demand for talent in the life sciences industry [32]. The International Mentorship Program (IMP), with the support of the International Mentorship Foundation for Higher Education (IMFAHE), has attracted talent and promoted the innovative development of young talents [33]. Young talented individuals can use their professional knowledge and skills to positively reduce SO_2 emissions from the industrial sector, thereby better safeguarding the safety and sustainable development of the ecological environment.

Through innovative policy gathering levels, the CIPCP can provide policy assurance for reducing SO_2 emissions from industrial sectors [34]. Studies have shown that climate institutions can strengthen the implementation of national climate policies and promote climate governance [35]. A review of the performance of the National Medium- and Long-Term Plan for Science and Technology Development (2006–2020) analyzed a series of achievements resulting from this policy. The SO_2 pollution tax policy can significantly reduce the concentrations of PM2.5 and SO_2 [36]. Policies can promote environmental protection and assist in implementing SO_2 emission reduction.

The CIPCP can provide financial support for reducing SO_2 emissions from the industrial sectors through venture capital gathering levels. Investment has introduced funding and technology for sustainable environmental development [37]. Chen et al. (2022) and Xu et al. (2021) demonstrated that foreign investment can influence SO_2 emissions [38,39]. China's investment has achieved tremendous achievements in ecological and environmental protection [40,41]. Venture capital plays a significant role in environmental protection, providing more funding and sufficient markets and resources for the industry to promote the reduction in SO_2 emissions and accelerate the development of ecological and environmental protection.

The CIPCP can provide technical support for reducing SO_2 emissions from industrial sectors through technology-gathering levels. Policies have a critical promoting role in the innovation and development of technology, providing necessary support and assistance for technological progress [42]. Studies have shown that metal–organic framework (MOF) technology can selectively remove SO_2, which benefits the environment and human health and contributes to sustainable development goals [43]. A new low-temperature adsorption process has been developed to remove SO_2 from exhaust gas. Technology is vital to reducing SO_2 emissions. Only by continuously developing and applying new technologies and promoting their popularization on a global scale can a comprehensive improvement in SO_2 emission reduction be achieved.

3. Methods

3.1. DID

The difference-in-differences (DID) method has been widely used in econometrics recently. The 2008 policy pilot for China's innovative cities is an exogenous policy shock caused by the industrial sector's SO_2 emissions, which can be seen as a "quasi-natural experiment". To use the DID model, it is necessary to ensure the randomness of the sample selection and parallel trend test [44]. To consider the time difference in the implementation of the CIPCP and to evaluate its impact on industrial sector SO_2 emissions scientifically, we followed the studies of Dong et al. (2019), Pei et al. (2019), and Popp (2006), and constructed the following regression model [45–47]:

$$SO_2\_Emission_{i,t} = \alpha + \beta Inno\_Policy_{i,t} + \gamma Control\_Variable_{i,t} + City\_Fixed + Year\_Fixed + \varepsilon_{i,t} \quad (1)$$

$SO_2\_Emission$ represents the amount of SO_2 emissions from a city's industrial sectors, *Inno_policy* represents the policy of the CIPCP, and *Control_Variable* is a set of control variables. *City_Fixed* represents city-fixed effects, *Year_Fixed* represents year-fixed effects, and ε is the error term. The estimated coefficient β measures the average difference in the SO_2 emissions of the city's industrial sector before and after implementing the CIPCP.

3.2. Parallel Trend Test Model

Since the implementation times of the CIPCP vary, it is necessary to set up separate dummy variables for the specific implementation times in each city. To test whether the experimental and control groups had similar trends before policy implementation, we employed a multi-timepoint DID model for parallel trend testing, as follows:

$$\begin{aligned} &SO_2\_Emission_{i,t} = \alpha + \beta_1 Before3_{i,t}{}' + \beta_2 Before2_{i,t} + \beta_3 Before1_{i,t} + \beta_4 Current_{i,t} \\ &+\beta_5 After1_{i,t} + \beta_6 After2_{i,t} + \beta_7 After3_{i,t} + \beta_8 After4_{i,t} + \beta_9 After5_{i,t} + \beta_{10} After6_{i,t} \\ &+\beta_{11} After7_{i,t} + \beta_{12} After8_{i,t} + \gamma Control\_Variable_{i,t} + City\_Fixed + Year\_Fixed + \varepsilon_{i,t} \end{aligned} \quad (2)$$

In the equation, the time dummy variables represent the observations for each pilot city n years before, during, and after implementing the innovative city pilot policy. The dummy variable was set to 1 for pilot cities and 0 for non-pilot cities.

3.3. Market Potential Measurement Model

In this study, we measured each city's market potential (*Market_pot*) using [48] as a metric. The calculation formula is as follows:

$$Market\_pot_i = \sum_{j \neq i} GDP_j / Space_{ij} + GDP_i / Space_{ii} \quad (3)$$

where GDP_j is the average GDP of city j from 2004 to 2007, $Space_{ij}$ is the geographic distance between city i and city j, and $Space_{ii}$ is the distance within city i, $Space_{ii} = 0.66 \times \sqrt{area_i/\pi}$, $area_i$, which is calculated as the city's land area (*Landi*) divided by its population (*Popi*).

3.4. Mediation Analysis Model

Based on the theoretical analysis presented earlier, to examine the mechanism by which the CIPCP affects industrial SO_2 emissions, we constructed the following mediation analysis model:

$$\begin{aligned} Inter\_Variable_{i,t} = \alpha + \phi Inno\_Policy_{i,t} + \gamma Control\_Variable_{i,t} \\ + City\_Fixed + Year\_Fixed + \varepsilon_{i,t} \end{aligned} \quad (4)$$

$$\begin{aligned} SO_2\_Emission_{i,t} = \ & \alpha + \theta Inno\_Policy_{i,t} + \delta Inter\_Variable_{i,t} \\ & + \gamma Control\_Variable_{i,t} + City\_Fixed + Year\_Fixed + \varepsilon_{i,t} \end{aligned} \quad (5)$$

In this model, the variable *Inter_Variable* represents the mediator variable, which is successively replaced by four variables reflecting the levels of talent agglomeration, innovation policy agglomeration, venture capital agglomeration, and technology agglomeration. The other variables remain unchanged. If the coefficients $\phi\delta$ are both significant, it indicates the presence of a mediating effect.

3.5. Variable Specification

The variable explained is the industrial SO_2 emissions (*SO_2_Emission*) level in China's cities. Industrial SO_2 emissions have been widely used as an indicator of environmental pollution in China and other countries [49]. The increase in city SO_2 emissions is mainly associated with the consumption of fossil fuels and is primarily due to the rapid development of city industries, particularly industrial activities [50]. This forms the basis for this study. We collected data on the level of industrial SO_2 emissions in 260 Chinese cities from 2004 to 2018. To ensure the reliability of the results, we converted the raw data into a standard unit to reduce the measurement error caused by differences in the original data.

The core explanatory variable is the virtual variable of the CIPCP (*Inno_policy*). We set cities that implemented the policy as the treatment group with a value of 1 and cities that did not implement the policy as the control group with a value of 0. We used the variable "*Form*" to represent the policy variable, setting the time before the policy implementation as 0 and the time after the implementation as *1* using the virtual variable "*Moment*". The interaction term of the policy variable and virtual variables interaction term is represented as "*Form* × *Moment*".

Controlling variables is a crucial aspect of scientific inquiry. To account for the impact of other city factors on industrial sector SO_2 emissions, this study selected the following variables as control variables: (1) Economic development level (*Economic_del*). Generally, the economic development level is associated with technological advancement, production efficiency, and an improved ecological environment, which may affect industrial sector SO_2 emissions. Some studies only use the GDP growth rate to measure economic development level [51], which is problematic. To address this issue, this study followed the authors of [52] in measuring the city's economic development level using the natural logarithm of actual per capita GDP, which reduces the impact of extreme values and heteroscedasticity. (2) Industrial structure (*Indust_stru*). According to the "Classification Regulation of Three Industries" issued by the National Bureau of Statistics of China in 2003, the first industry refers to agriculture, the second to construction, and the third to services and circulation [53]. A proper industrial structure can promote rational resource utilization and reduce the environmental impact of economic activities [54,55]. The industrial structure may also affect the industrial sector's SO_2 emissions. Following Wei et al. (2015), this study used an industrial structure upgrading index to represent a city's industrial structure changes [56]. (3) Financial support (Finance). Financial support can drive green development and promote economic growth [57,58]. It can reflect a city's capital accumulation and resource utilization efficiency, provide specific financial support to the industrial sector, and reduce industrial sector SO_2 emissions. Following Jun et al. (2022), this study used the ratio of various loan balances of financial institutions to GDP to measure a city's financial support [52]. (4) Level of informatization (*Informatization_le*). Kuzior et al. (2023) found that innovative technology can improve socioeconomic and environmental conditions after the introduction of informatization [59]. The informatization level may promote the modernization of industrial equipment and reduce the industrial sector's SO_2 emissions. This study measured the level of city informatization using the number of internet users. (5) Degree of marketization. After China acceded to the World Trade Organization (WTO) in 2001, market-oriented economic reform promoted continuous improvement in the degree of marketization in China [60]. A high degree of marketization reflects a high resource allocation efficiency, leading to more effective use of resources and capital in the entire market system, improving the efficiency of economic operation, and promoting innovation and entrepreneurial ability. Enhancing the degree of marketization can also encourage the integration of the market. Following Wang and Qian (2011), this study used the ratio of GDP to government budget to measure the degree of marketization [61].

3.6. Data Sources

Between 2004 and 2018, a total of 276 pilot cities were designated by the National Development and Reform Commission of China. These cities encompass a range of economic and social development stages and are confronted with distinct developmental tasks, thereby endowing them with a significant level of representativeness. The principal objectives of the pilot cities are fundamentally aligned, aiming to curb greenhouse gas emissions, explore green and low-carbon development models, and spearhead and exemplify national endeavors in low-carbon development. This study employed panel data from 276 Chinese cities from 2004 to 2018 to evaluate the impact of China's innovation-driven city development pilot policy on reducing the industrial sector's SO_2 emissions (as shown in Figure 1). To ensure the accuracy of the results, we selected 71 pilot cities (excluding Lhasa city, two county-level cities, and four municipalities directly under the central government) and excluded cities with severely missing data. The data were obtained from the "China City Statistical Yearbook", "China Science and Technology Statistical Yearbook", and various provincial and municipal statistical yearbooks. Linear interpolation was used to fill in missing data.

Figure 1. The case study area (the numbers represent the amount of innovation pilot cities in each province).

4. Empirical Analysis

4.1. Baseline Regression

Table 1 presents the regression results on the effect of the CIPCP on SO_2 emissions in the industrial sector. Column (1) reports the regression results controlling for city and year-fixed effects, while column (2) adds the control variables to the regression. The results show that, in both regression specifications, the coefficient of *Inno_policy* is significantly negative, indicating that the CIPCP has significantly reduced SO_2 emissions in the industrial sector.

4.2. Robustness Check

4.2.1. Assumption of Parallel Trends

As shown in Figure 2, the coefficient estimates of the pre-policy relative time dummies are primarily insignificant and small. Wang et al. (2018) found that, from 2009 to 2013, the SO_2 concentration in northern and southern China was affected by different factors [62].

The SO_2 concentration north of China was mainly due to industrial emissions, while meteorological southern China factors had a more significant impact on the reduction in SO_2 concentration than industrial emissions. As most of the CIPCPs were implemented in southern China, these policies were subject to more significant weather-related influences. We further conducted placebo tests, and all policies passed the test, confirming the validity of the assumption of parallel trends. In Figure 1, the pilot policies decreased industrial SO_2 emissions after implementation, but the effect was not stable. However, two years after policy implementation, the coefficient became significantly positive and continued to increase, indicating that the CIPCP can promote a reduction in industrial SO_2 emissions with a lag effect.

Table 1. Regression results.

Variable	(1)	(2)
	SO_2_Emission	*SO_2_Emission*
Inno_policy	−1.4384 ***	−1.4199 ***
	(−3.4134)	(−3.4446)
Control Var	no	yes
Fixed effect	yes	yes
Observations	4140	4140
R^2	0.3767	0.3875

Note: ***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses are clustering robust standard errors.

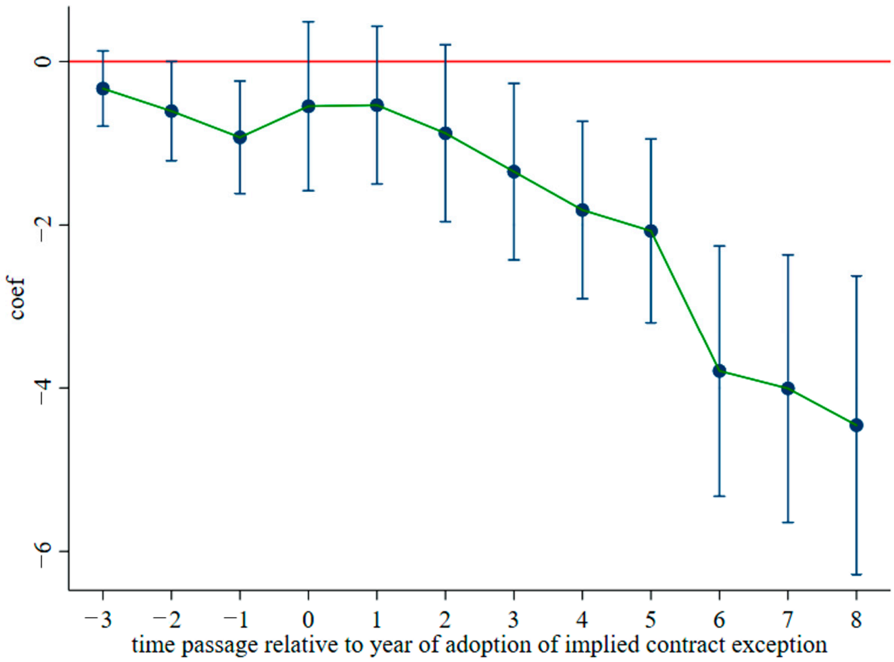

Figure 2. The assumption of parallel trends.

As shown in Figure 3, before the implementation of the policy in 2010, there was a significant difference in SO_2 emissions between pilot and non-pilot cities. After implementing the CIPCP, the SO_2 emissions in pilot cities showed an upward trend for nearly a year, indicating a particular lag effect of the policy. Subsequently, the SO_2 emissions in pilot cities decreased significantly compared to non-pilot cities, and the gap continued to narrow, further confirming the effectiveness of the CIPCP in reducing industrial SO_2 emissions.

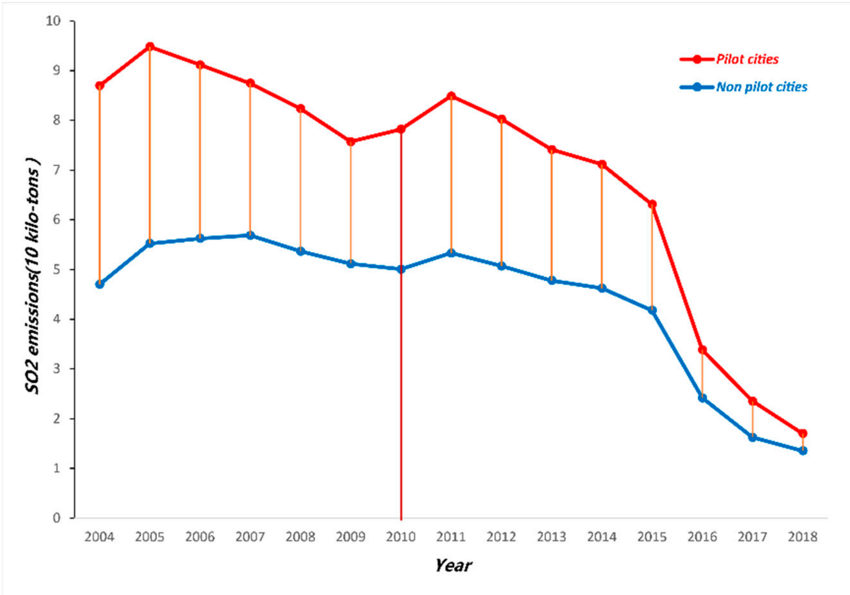

Figure 3. Emissions of SO_2 from the pilot and non-pilot cities.

4.2.2. PSM-DID Model Testing

To ensure the robustness of our model, we employed the PSM-DID estimation method and addressed the issue of a selection effect in our data. PSM is suitable for cross-sectional data, while DID is appropriate for panel data. The existing literature offers two approaches to resolve this issue: converting panel data into cross-sectional data to construct cross-sectional PSM or adopting the period-by-period matching method, following [63]. The cross-sectional and yearly PSM results are presented in columns (1) and (2) of Table 2, respectively. The *Inno_policy* coefficient is significantly negative in both models and consistent with the sign and significance of the benchmark regression results, indicating the significant effect of the CIPCP on reducing industrial SO_2 emissions and the robustness of our findings.

Table 2. The entrepreneurial city pilot policy impact.

Variable	(1)	(2)	(3)
	Cross-Sectional PSM-DID	**Annual PSM-DID**	**Excluding Entrepreneurial Policies**
Inno_policy	−1.3585 *** (−3.2782)	−1.3158 ** (−2.4737)	−1.4257 ** (−3.2505)
Ent Policy			0.0172 (0.0421)
Control Var	yes	yes	yes
Fixed effect	yes	yes	yes
Observations	3919	3087	4140
R^2	0.4035	0.4074	0.3875

Note: ***, ** and * denote significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses are clustering robust standard errors.

4.2.3. Controlling for Other Policy Effects

We selected the CIPCP as our focus to control other policy effects. By adding the virtual variable of the implementation time of this policy into the regression model, we excluded its potential impact on our results. As shown in column (3) of Table 2, the *Inno_policy* coefficient is −1.4257 and significantly negative at the 10% level, indicating that the CIPCP significantly reduces industrial SO_2 emissions. The policy has driven city entrepreneurship and promoted innovation consciousness, further supporting the development of green and environmentally friendly equipment in the industrial sector and accelerating the reduction in SO_2 emissions, and the results are robust.

4.2.4. Placebo Test

Although this study controlled for relevant variables that may affect industrial SO_2 emissions in a quasi-natural experiment, it is still possible that unobserved city-specific factors interfered with the results. To address this issue, this study followed Liu and Lu (2015) and randomly generated both a pseudo-treatment group dummy variable [64], "*Form*", and a pseudo-policy dummy variable, "*Moment*", for the 260 sample cities in 500 random draws. The results indicate that the generated regression coefficients are mostly centered around 0 and have *p*-values mostly above 0.1 (shown in Figure 4). In contrast, the estimated coefficient for the actual policy is −1.4199, which falls outside the range of the generated regression coefficients. This suggests that unobserved city-specific factors did not interfere with the results and that the conclusion of this study, that the CIPCP has a significant and robust effect on reducing industrial SO_2 emissions, passed the placebo test.

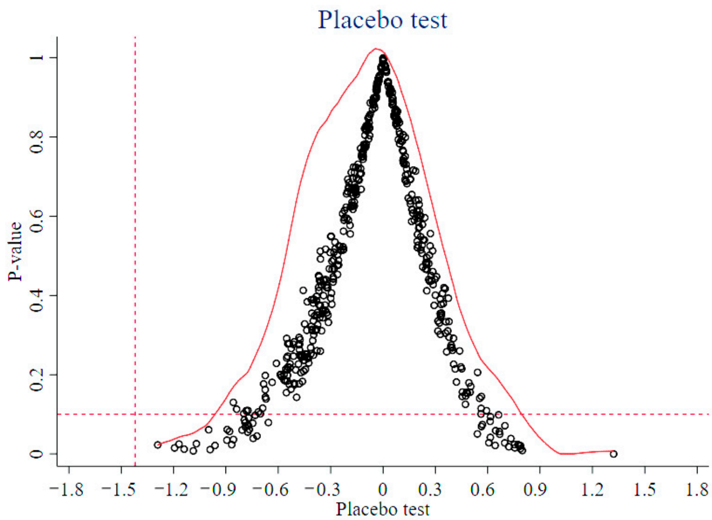

Figure 4. The placebo test.

5. Results

5.1. Effects of City Heterogeneity

The heterogeneity of this study primarily examines whether the effectiveness of the CIPCP in reducing industrial SO_2 emissions varies based on the size of the city, the region where it is located, and the city's market potential.

5.1.1. Heterogeneity of the City Size

This study used a set of dummy variables (*Grade*) to represent the city size. According to the 2020 China Census County Data compiled by the Leading Group Office of the Seventh National Population Census of the State Council, the 7 super-large cities, 14 extra-large cities, and 14 type I large cities in China were denoted by the dummy variable 1, while other cities were denoted by the dummy variable 0. The interaction term between the city size dummy variable (*Grade*) and the pilot policy dummy variable (*Inno_policy*) was added to the baseline regression model. As shown in column (1) of Table 3, the coefficient of the *Grade* × *Inno_policy* interaction term is −1.4337 and significant at the 10% level, indicating that the CIPCP has a stronger effect on reducing industrial SO_2 emissions in large cities. Figure 5 illustrates the effect of the pilot cities on industrial SO_2 emission reduction in large and small cities (the arrows in the figure represent the gap in the emission reduction capacity of small cities compared to large cities). Before 2010, large cities had higher levels of SO_2 emissions than small cities. However, the gap gradually narrowed after the policy was implemented in 2010, and the reduction effect in large cities was more evident. Large cities have relatively advanced new energy and environmental technologies, a more vital awareness of ecological protection among citizens, and higher emission standards for industrial sector emissions, contributing to the reduction in industrial SO_2 emissions.

Table 3. The impact of market potential on SO_2 emissions.

Variable	(1)	(2)	(3)
	Grade	***Hu_line***	***Market_pot***
Grade × *Inno_policy*	−1.4337 *		
	(−1.8546)		
Hu_line × *Inno_policy*		2.2399 **	
		(2.0352)	
Market_pot × *Inno_policy*			−1.9385 **
			(−2.4855)
Control Var	yes	yes	yes
Fixed effect	yes	yes	yes
Observations	4140	4140	4005
R^2	0.3910	0.3907	0.3988

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses are clustering robust standard errors.

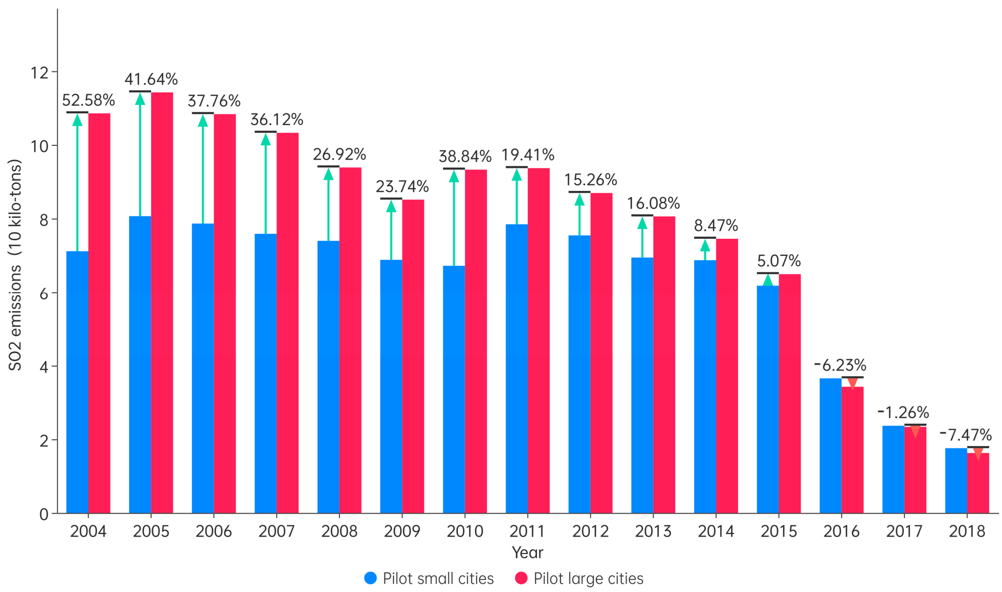

Figure 5. Industrial SO_2 emission reduction in large and small cities.

5.1.2. Heterogeneity in City Regional Characteristics

The *Hu Huanyong* Line (*Hu_Line*) is used to restrict regional characteristics in China. This line divides the country into two parts, the east–west and the north–south, with high urbanization and population density in the southeastern region and low urbanization and population density in the northwestern region [65]. Such regional characteristics may have different impacts on the effectiveness of the CIPCP in reducing industrial SO_2 emissions. We constructed a virtual variable for the *Hu_Line* to investigate this. Specifically, cities located southeast of the *Hu_Line* were assigned a value of 0, while those to the northwest were assigned a value of 1. We incorporated this and the virtual policy variable into the baseline regression model. The results are shown in Table 3, column (2). The coefficient for the interaction term of *Hu_Line* and *Inno_policy* is 2.2399, which is significant at the 5% level. As shown in column (2) of the baseline regression Table 1, the coefficient of *Inno_policy* is −1.4337. This implies that the CIPCP has a more significant effect in reducing industrial SO_2 emissions in cities southeast of the *Hu_Line* than those found in the northwest. Figure 6 illustrates the reduction in industrial SO_2 emissions among pilot cities in different regions of China (The arrows in the figure represent the gap in the emission reduction capacity of cities in the Southeast region compared to cities in the Northwest region). Notably, the emissions from industrial sources in pilot cities located southeast of the *Hu_Line* have been consistently lower than those located northwest since the policy was implemented in 2010. This may be attributed to the higher economic and technological development in the southeastern cities, which decreases towards the northwest, and its influence on reducing industrial SO_2 emissions in Chinese cities.

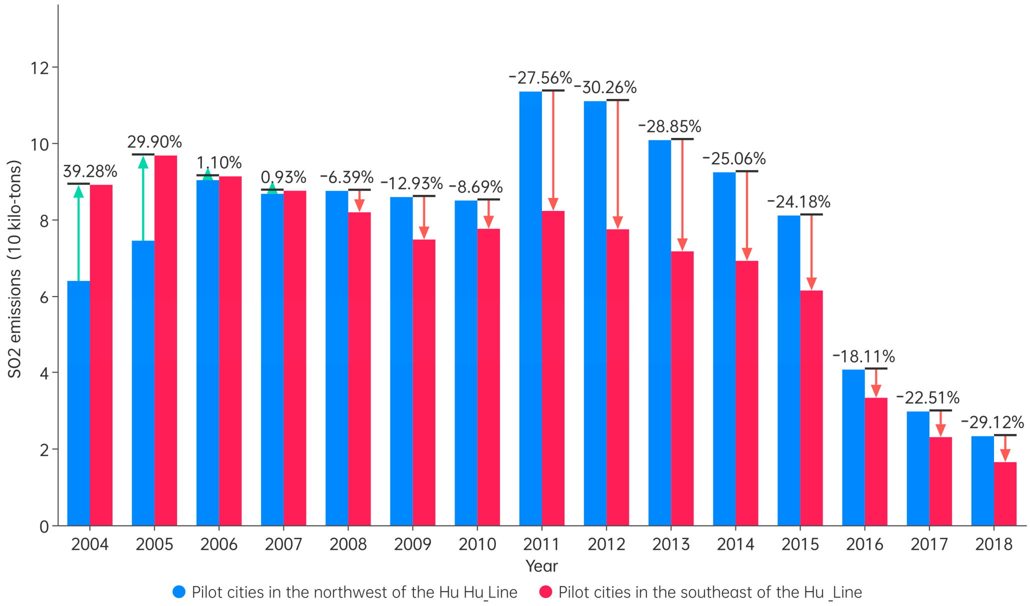

Figure 6. The reduction in industrial SO_2 emissions among pilot cities in different regions of China.

5.1.3. Heterogeneity in Market Potential

This study represented the market potential by the variable "*Market_pot*." There is a relationship between market potential and technological innovation; cities with more significant market potential can promote technological innovation under certain conditions. Market potential implies unmet demand and potential opportunities, and through technological innovation, the industry can produce more products to meet consumer needs. For SO_2, technological innovation can reduce industrial SO_2 emissions by improving combustion equipment, fuel quality, production processes, and other means. The results, shown in column (3) of Table 3, indicate that the coefficient of the $Market\_pot \times Inno\_policy$ interaction term is -1.9385 **, which is significant at the 5% level, indicating that the effects of the CIPCP on industrial SO_2 emissions differ significantly among cities with different market potentials. In cities with a higher market potential, the reduction in industrial SO_2 emissions is more significant than in those with a lower market potential.

Figure 7 compares industrial SO_2 emissions in pilot cities with different market potentials (the arrows in the figure represent the difference in emission reduction capacity between the low-market potential pilot cities and the high-market potential pilot cities). The pilot cities with a higher market potential had higher industrial SO_2 emissions than those with a lower market potential before 2010. Still, they gradually reduced their emissions after 2010, demonstrating that cities with a higher market potential have more potential for lowering industrial SO_2 emissions.

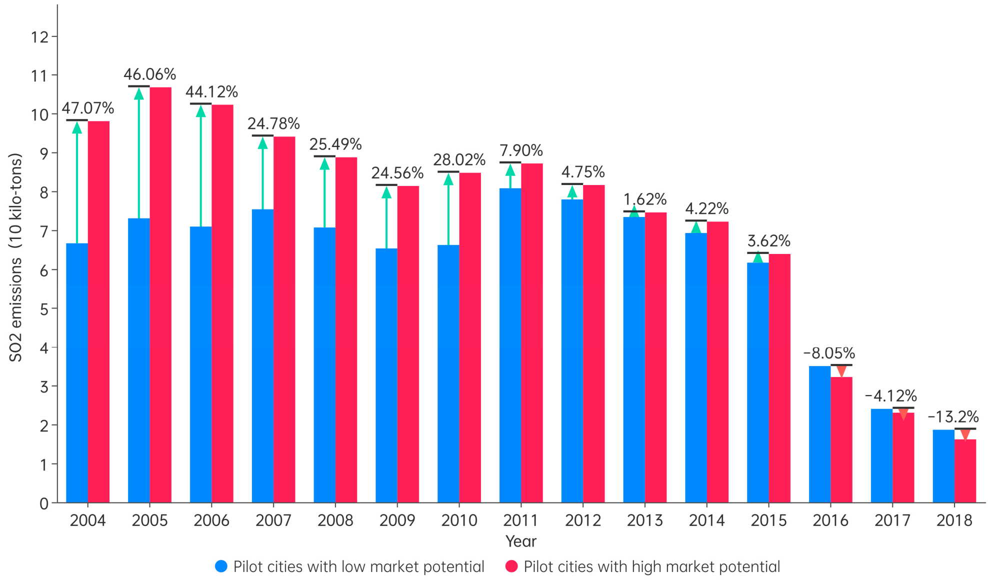

Figure 7. Industrial SO_2 emissions in pilot cities with different market potentials.

5.2. Mediating Effects of Pilot Policies

In this study, we selected talent concentration level, innovation policy concentration level, venture capital concentration level, and technology concentration level as the testing variables of the mechanisms [52]. Our main objective was to investigate whether the CIPCP would affect talent concentration, innovation policy concentration, venture capital concentration, and technology concentration levels and subsequently impact the reduction in the industrial sector's SO_2 emissions.

Regarding talent concentration level, we defined individuals engaged in scientific research, technological innovation, computer services, software development, and related fields as knowledge-intensive personnel and expressed the proportion of such personnel among the total employed population in a city as the talent concentration level [66]. This approach has a certain level of rationale and reliability. As shown in the first column of Table 4, the *Inno_policy* coefficient was significantly positive at the 1% level, indicating that the CIPCP significantly promoted talent concentration level. The results in the second column of Table 4 indicated that both the *Inno_policy* and Talents coefficients were highly negative, suggesting that the talent concentration level significantly reduced industrial SO_2 emissions. Figure 8 shows an inverse relationship between industrial SO_2 emissions and talent concentration level, demonstrating that the talent concentration level could reduce industrial SO_2 emissions. Talent concentration could improve city resource allocation, optimize industrial equipment, enhance awareness of industrial environmental protection, promote technological innovation, and provide new ideas for industrial SO_2 emission reduction.

5.2.1. Innovation Policy Aggregation Level

Regarding the innovation policy aggregation level, we collected the number of innovation policies announced by 260 Chinese cities from 2004 to 2018 and adopted several retrieval methods to ensure the accuracy of the number of innovation policies in each city. As shown in the third column of Table 4, the *Inno_policy* coefficient was significantly positive at the 1% level, indicating that the CIPCP significantly promoted innovation policy concentration level. The results in the fourth column of Table 4 indicate that both the *Inno_policy* and *Policy* coefficients were significantly negative, suggesting that innovation policy concentration level significantly reduced industrial SO_2 emissions.

Table 4. The impact of talent aggregation level results.

Variable	(1)	(2)	(3)	(4)
	Talent	*SO_2_Emission*	*Policy*	*SO_2_Emission*
Inno_policy	0.38 *** (2.6957)	−1.3103 *** (−3.1524)	6.9622 *** (6.3982)	−0.9576 ** (−2.2366)
Talent		−20.6505 ** (−2.4646)		
Policy				−0.0619 *** (−3.5307)
Control Var	yes	yes	yes	yes
Fixed effect	yes	yes	yes	yes
Observations	3900	3900	3900	3900
R^2	0.72	0.4131	0.3304	0.4201

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses are clustering robust standard errors.

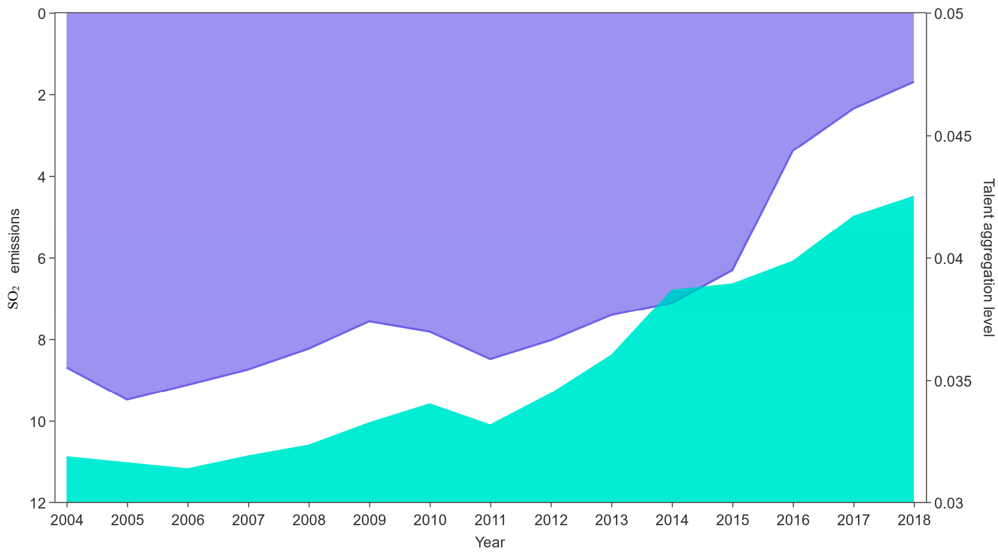

Figure 8. Relationship between industrial SO_2 emissions and talent concentration level.

Figure 9 shows an inverse relationship between industrial SO_2 emissions and the number of innovation policies, further demonstrating that innovation policies reduced industrial SO_2 emissions. The emission trading mechanism (ETS) in innovation policies restrained industrial sectors from emitting pollutants, reduced fossil fuel consumption, and improved energy utilization efficiency, ultimately achieving industrial SO_2 emission reduction.

5.2.2. Agglomeration of Risk Investment

Risk investment is one of the critical indicators for evaluating city innovation, entrepreneurship, and economic development. It provides insights into the economic and innovative environment of cities. As shown in column (1) of Table 5, the *Inno_policy* coefficient is significantly positive at the 5% level, indicating that the CIPCP promoted the accumulation of risk investment. The coefficients of *Inno_policy* and *Risk_inves* in column (2) of Table 5 are both significantly negative, suggesting that the collection of risk investment has significantly reduced industrial SO_2 emissions. Figure 10 displays a reverse relationship between the amount of SO_2 emissions and the aggregation of risk investment, represented by coordinates. Type points 1.0 and 2.0 indicate that risk investment can reduce SO_2 emissions. This finding is consistent with the conclusion obtained by the previous scholar. Risk investment can promote the development and application of environmental protection technology, improve production efficiency, reduce emissions, and make environmental protection an essential consideration for industrial development, thus promoting the reduction of industrial SO_2 emissions.

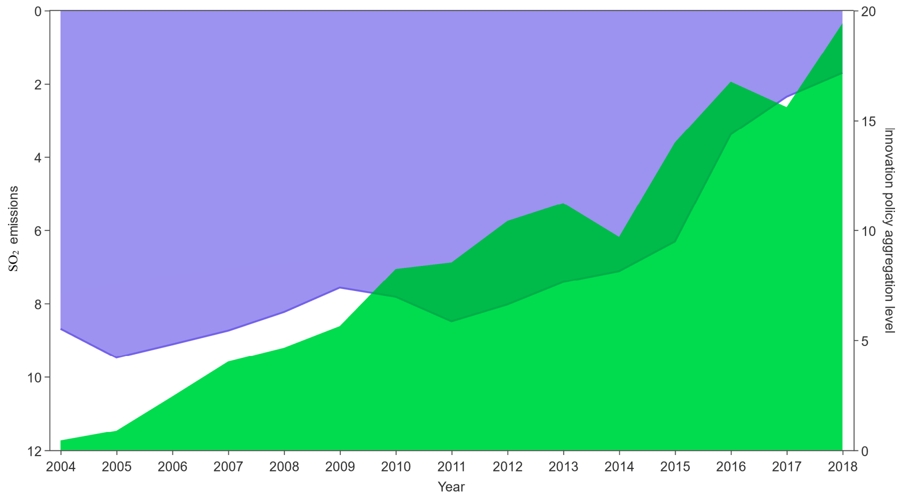

Figure 9. Relationship between industrial SO_2 emissions and the number of innovation policies.

Table 5. Mechanism verification.

Variable	**(1)**	**(2)**	**(3)**	**(4)**
	Risk_inves	***SO_2_Emission***	***Technology***	***SO_2_Emission***
Inno_policy	0.304 ** (2.2390)	−1.4067 *** (−3.4201)	0.6993 ** (5.3436)	−1.2473 *** (−2.9808)
Rsk_inves		−0.4338 * (−1.6649)		
Technology				−0.2467 * (−1.7528)
Control Var	yes	yes	yes	yes
Fixed effect	yes	yes	yes	yes
Observations	4140	4140	4140	4140
R^2	0.69	0.3883	0.3726	0.3900

Note: ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively. Values in parentheses are clustering robust standard errors.

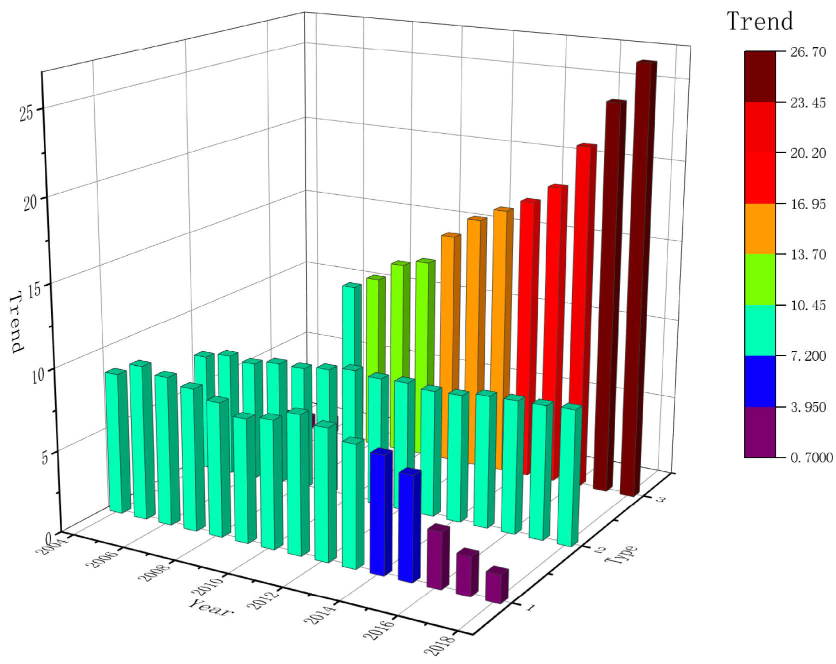

Figure 10. Relationship between the amount of SO_2 emissions and the aggregation of risk investment.

5.2.3. Agglomeration of Technology

Technology is an essential component of city development that not only improves the efficiency and management of cities but also brings more creativity, making significant contributions to the development of cities. As shown in column (3) of Table 5, the *Inno_policy* coefficient is significantly positive at the 5% level, indicating that the CIPCP has promoted technology agglomeration. The coefficients of *Inno_policy* and *Technology* in column (4) of Table 5 are both significantly negative, meaning that technology accumulation significantly reduced industrial SO_2 emissions. Figure 10 displays a reverse relationship between the amount of SO_2 emissions and the proliferation of technology, represented by coordinates. Type points 1.0 and 3.0 further indicate that technology can reduce SO_2 emissions. Technology development enables the industry to achieve the goal of green and sustainable development while ensuring production capacity and injecting new ideas and vitality into long-term economic growth. Efficient, clean, and low-consumption technologies play a positive role in protecting and improving the environment, thereby promoting the reduction of industrial SO_2 emissions.

6. Conclusions

SO_2 is a common air pollutant, and reducing its emissions significantly improves environmental quality and promotes the sustainable development of the global economy and society. Based on panel data from 260 cities in China between 2004 and 2018, this study employed a multiple timepoint difference-in-differences (DID) approach to systematically examine the effects of the CIPCP on the industrial sector's SO_2 emissions. The findings are as follows: (1) The CIPCP significantly reduced the industrial sector's SO_2 emissions. This conclusion remains valid after various robustness tests. (2) The heterogeneity analysis of cities shows that the effectiveness of the CIPCP in reducing the industrial sector's SO_2 emissions is related to city market potential, city size, and regional differences, with more potent effects observed in large cities or cities with more significant market potential, particularly in the southeastern region of China. (3) The heterogeneity analysis of pilot policies indicates that the positive impact of the CIPCP on reducing industrial sector SO_2 emissions is achieved through talent concentration levels, policy concentration levels, venture capital concentration levels, and technology concentration levels.

Based on the above conclusions, this paper proposes the following policy recommendations: (1) Strengthen the environmental protection system in the CIPCP. Establish a sound monitoring and evaluation mechanism for the CIPCP and restrict industrial pollutant emissions. Promote green technology innovation, strengthen research and development of sulfur removal technology in the industrial sector, and improve energy utilization efficiency. (2) Emphasize the role of the CIPCP in talent aggregation level, innovation policy aggregation level, risk investment aggregation level, and technology aggregation level. (3) The CIPCP needs to consider the differences between cities. Regional differences lead to varying degrees of industrial SO_2 reduction. The CIPCP should be tailored to local conditions and rationally planned, with the leading role of developed eastern regions in driving the development of the less developed western regions, ultimately achieving balanced development between eastern and western China. Policies should be developed based on different cities' actual situations and needs. For large cities, the focus should be on maintaining the prevention and control of industrial pollution, while for small cities, environmental technology research and development should be strengthened.

Although the study explored the factors influencing industrial sector SO_2 emission reduction through innovation, the analysis was limited to data from 276 Chinese cities, warranting the need for research with broader geographical coverage. Additionally, the study did not delve into the specific mechanisms of innovation implementation. Future research should conduct comparative analyses across countries/regions, employ qualitative methods to understand implementation challenges, and investigate the long-term impacts of SO_2 emission reduction on the environment, health, and economy. These efforts would enhance policy formulation and address the limitations of this study.

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