



Structural Features of China's Industrial Pollution Inequality: A Spatial-Temporal Distribution Perspective

Jin Luo^{1,2†}, Yuan Wang^{1,2,3*†}, Lin Zhu⁴, Pei-Pei Jiang^{1,2}, Yan-Min He⁵ and Ting-Ting Hao³

¹Institute of Geography, Fujian Normal University, Fuzhou, China, ²Key Laboratory for Humid Subtropical Eco-geographical Processes of the Ministry of Education, School of Geographical Sciences, Fujian Normal University, Fuzhou, China, ³State Key Laboratory of Pollution Control and Resource Reuse, School of Environment, Nanjing University, Nanjing, China, ⁴Nanjing Institute of Environmental Sciences, Ministry of Ecology and Environment, Nanjing, China, ⁵Faculty of Economics, Otemon Gakuin University, Osaka, Japan

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*Correspondence:

Yuan Wang
y.wang@fjnu.edu.cn
ywang@njnu.edu.cn

[†]These authors share first authorship

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With growing concerns about the allocation inequality of environmental benefits and pollution, it is crucial to investigate whether a special characteristic of China's environmental inequality has emerged. The present study aims to elucidate the regional spatial features of industrial pollution inequality (IPI) (waste gas, wastewater, and solid waste measured by the Theil index separately) and their relevance to national territorial space planning strategies. Furthermore, we make a novel attempt to develop an integrated framework that employs a developed-Kaya identity with the Logarithmic Mean Divisia Index method to uncover the driving force of IPI disparities. We make use of the data published recently by the provincial panel of China, during the period 2000–2015. Based on this information, we found notable spatial-temporal heterogeneity in China's IPI, highly correlated to China's core national territorial space planning strategy, the "T-shaped" spatial development strategy. The empirical results support the "structural features" hypothesis in IPI for China. In particular, the Coastal Region has a great edge in industrial pollution equality. In most provinces in the Inland Corridor along the Yangtze River, the trend of IPI has been alleviated to some extent. However, provinces further inland that are off-side the two axes of "T-shaped" spatial development strategy have to respond to the two-fold challenge of the exacerbated trend in IPI both within and between the regions. Our findings also indicate that the effect of technological inequality is the main driving force for IPI in the earlier stage of development. However, effects of economic inequality together with that of economic structure inequality manifest in the middle or transition period and the economic inequality effect is the determinant in the later stage of development. Additionally, contributions of size effect and inequality effect are changeable over development process, economic inequality effect outweighs the economic size effect

Abbreviations: CO, carbon monoxide; CO₂, carbon dioxide; CR, the coastal region; GDP, gross domestic product; ICYR, inland corridor along yangtze river; IDA, index decomposition analysis; IPAT, environmental impact, population, affluence, and technology; IPI, industrial pollution inequality; ISW, industrial solid waste; IWGSO₂, industrial sulfur dioxide; IWW, industrial wastewater; LMDI, logarithmic mean divisia index; NO₂, nitrogen dioxide; O₃, ozone; OR, other regions; PM_{2.5}, PM₁₀, particulate matter smaller than 2.5 mm, 10 mm; SO₂, sulfur dioxide.

for IPI in more developed districts or districts in higher developing phases. These findings may help the government incorporate environmental equality goals into regional policies and contribute to the emerging literature on environmental inequality.

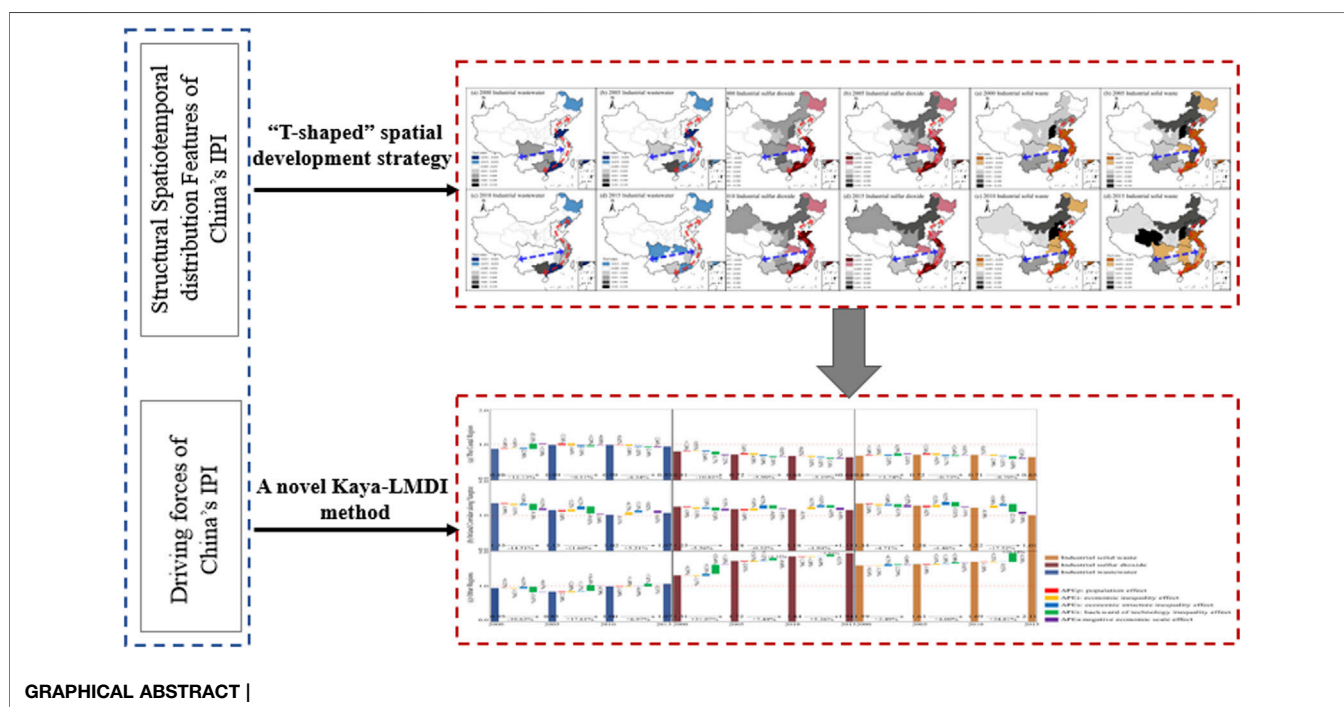
Keywords: industrial pollution, spatial-temporal distribution, environmental inequality, T-shaped spatial development strategy, China

INTRODUCTION

Inequality impedes long-term social and economic development (Rashid et al., 2019). In the wake of the COVID-19 pandemic, existing inequalities had been deepened (FAO, 2020), which significantly undermine the overall implementation of the 2030 Agenda for Sustainable Development (UNDP, 2019). In addition to economic inequality, environmental inequality is usually concealed and overlooked under economic development (Sovacool et al., 2016; Jenkins et al., 2017; UNDP, 2019). Regarded as “slow violence” (Nixon, 2011), environmental degradation significantly affects the wellbeing of the poor more than that of the rich. That is, some groups consume far more of our environmental resources and have more access to information and technology than others, while some groups suffer from more serious environmental pollution and have less access to information and technology than others (Clayton, 2000). Meanwhile, low-income and poor social capital populations incline to live in polluted areas where the rent is relatively low (Temper et al., 2018) because of lack of choice due to economic constraints (Flanquart et al., 2013), thus, further exacerbating the inequality. It is noteworthy that the environmental crisis can aggravate social inequality by placing environmental inequality over economic inequality

and may induce an inequality Matthew effect (Yang and Yang, 2020). Conversely, reduction in inequality may also improve environmental performance (Rao and Min, 2018).

The inequality in China has been a hot issue of international concerns and disputes as it is one of the fastest-growing economies (Xie and Zhou, 2014; Wu et al., 2017). As China is stepping toward a new era, the Chinese government clarifies that Chinese society's principal contradiction lies in the unbalanced and inadequate development and people's calling for a better life (Xi, 2018). Unlike the racial or ethnic factors that are mainly responsible for western developed countries' environmental inequality (Tessum et al., 2019; Nijman and Wei, 2020), previous studies found that the economic factors and industrial development factors are more accountable for environmental inequalities in China. Inequality in the industry sector is significantly higher than in the service sector (Xiao et al., 2019). Rapid industrialization is the engine for China's economic growth and the source of environmental burdens and conflicts. However, these benefits and burdens are allocated disproportionately among regions. The periphery may face more negative impacts than the center (Althouse et al., 2020), in China, less-developed inland regions gain less economic benefits and emit more industrial pollutants than more-developed coastal regions (Ma, 2010; Mi et al., 2020; Yang et al., 2020). The coastal regions emits considerably lower air



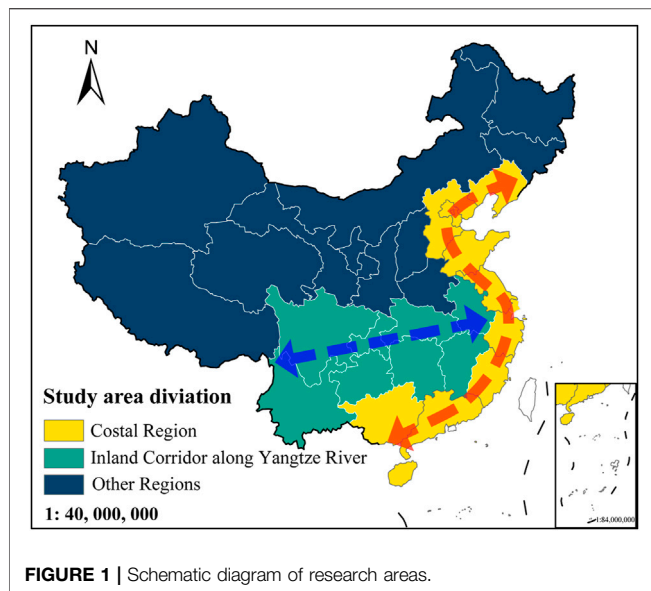
emissions pollutants than the average level of the country (Gu et al., 2013; Liang et al., 2016; Zhao et al., 2019). The annual population-weighted-average values of SO₂, PM₁₀, PM_{2.5}, CO, NO, and O₃ in northern China are about 96.7%, 58.9%, 40.4%, 38.1, 24.6, and 5.9% higher than in southern China during the period 2014–2016, respectively (Song et al., 2017). Furthermore, less-developed regions in the middle-western area of China have lower reduction potential and deal with higher unit abatement costs with their limited budgets. Even though many excellent case studies have been done, many of them have focused on the inequality of CO₂ (Chen et al., 2016; Chen et al., 2017; Fang et al., 2018; Cheng et al., 2021). On the one hand, most of the limited discussions of industrial pollutant inequality have been conducted separately for the single categories of industrial waste gas (Dong et al., 2015; Zhang et al., 2018c; Azimi et al., 2019; Cao et al., 2019; Guan et al., 2019; Zhao et al., 2019), industrial wastewater or water resources (Zhang and Anadon, 2014; Yao et al., 2018), and industrial solid waste (Ma et al., 2016). The only two comprehensive discussions of IPI have conducted the analysis over a very short period of time. One study was conducted for 2012 (Zhang et al., 2018b), while the other study was conducted for 2005 and 2006 (Ma et al., 2016). Thus, it is difficult to compare the differences and commonalities in the changes of inequalities in different categories of IPI on temporal and spatial scales. On the other hand, there has been little discussion of the relationship between structural forces (e.g., national strategies) and environmental inequality in China. Former spatial variations analyses have generally depended on the geographic orientation of China, which conventionally divides the study area into three parts: northern region, central region, and southern region (Gu et al., 2013; Liang et al., 2016). Some studies divided it more specifically into seven regions: northeast, north, northwest, east, central, southwest, and south regions (Song et al., 2017; Guan et al., 2019; Zhao et al., 2019). However, over the past 40-odd years, China's development strategy has been continually adjusted and optimized, especially the Yangtze River economic belt's rapid development. Previous ways of spatial division fall short of considering the substantial influence of the national strategy force in China and may no longer be suitable to cope with current problems. The traditional way of dividing regions may mask the structural features of the spatial distribution of China's IPI.

In light of the remarkable economic inequality, Xie (2010) and Feng (2008) have proposed a hypothesis that structural forces attributable to the Chinese political system rather than individual forces originating from family structure and race/ethnicity play a dominant role in China's income inequality. We assume that there exists a similar "structural forces-driven" hypothesis for environmental inequality in China, thus resulting in a special spatial-temporal distribution features of IPI. Our study attempts to test the "structural spatial-temporal distribution features" of IPI associates with the national territorial space planning strategy in China. As an important theoretical reference for the national territorial space planning strategy in China, the "T-shaped" spatial strategy (Lu, 2001) considers the Yangtze River corridor and coastal region as the axes of national economic

development, which developed upon the point-axis system theory first proposed by Lu Dadao in the year of 1984. Actually, the coastal region has benefited from the strategy and led China's development since the reform and opening up of the economy in the past 4 decades. The Chinese government made it a national strategy to further develop the Yangtze River economic belt and took the concept of eco-priority as a guiding principle for development in 2014 (The State Council of the People's Republic of China, 2014). By 2015, the GDP and population in these two regions accounted for 81.6% and 76.3% of the whole country, respectively (National Bureau of Statistics of China, 2000–2015a). Thus, examining whether the spatial-temporal distribution of China's IPI is highly correlated to the "T-shaped" spatial development strategy give a clue to understand the correlations between "structural force" and IPI. In line with this, all provinces in our study are divided into three parts: the Coastal Region (CR), Inland Corridor along Yangtze River (ICR), and Other Regions (OR), the first two of which correspond to the two axes of the "T-shaped" spatial development strategy. From the spatial perspective, we test the heterogeneity in IPI among regions under districts with different policies. From the temporal perspective, we check the coherence between IPI and the application of corresponding policies in different regions over different periods. The incorporation of the "T-shaped" spatial development strategy permits us to investigate the new incarnation of Chinese environmental inequality and test the correlation between environmental inequality and the "structural force" of these new changes and strategies.

The analysis of inequality has been developed for a long time, and there are several commonly used analytic approaches to measure it, such as the Gini coefficient (Gini, 1912), the Theil index (Theil, 1967), the Atkinson index (Atkinson, 1970), and the Variation coefficient. All these indices are closely related to the Lorenz curve; however, they present different properties of particular sensitivity and show different results regarding inequality changes according to how these differences are aggregated (Duro, 2012). Among them, the Gini index is more sensitive to the mean, while Atkinson or Theil index has more sensitivity to the changes in the lower ranks of the distribution. Thus, in the case of environmental inequality, Atkinson or Theil family of indexes would more attractive than the Gini index because of their ability to bring out differences in regions with lower levels of pollution (Heil and Wodon, 1997; Duro, 2012). Furthermore, with the capability to analyze the allocation of within-regional and between-regional environmental burden (Duro and Padilla, 2008), the Theil index is an appropriate inequality measurement that meets our research needs. Adopting the most recent provincial panel data from 2000 to 2015, we attempt to quantify the regional spatial features of China's industrial emissions (wastewater, waste gas, and solid waste) using the Theil index approach.

To further investigate what forces have driven the "structural features" of IPI in China and to what extent, there is a need to analyze the contributions of these multiple factors. IPAT (environmental impact, population, affluence, and technology) identity is a traditionally analysis framework to study factors impact on the environment (Ehrlich and Holdren, 1971).



However, the IPAT identity has a drawback that it considers only size effect and it is short of analyzing structural effect. This problem is solved by the Kaya identity (Kaya, 1990), for it is a ratio multiplication equation that could consider the structural effect as a ratio of two factors. In view of the fact that firms and individuals have different production and consumption behavior patterns, scholars have paid attention to the relationship between environmental inequality and population structure, such as age structure (Zagheni, 2011); and/or economic structure, such as industrial structure (Remuzgo and Sarabia, 2015). To analyze the contributions of factors causing environmental inequality, a number of decomposition methodology have been proposed and developed. Heil and Wodon (1997) applied the decomposition of the Gini index, which is proposed by Yitzhaki and Lerman (1991), to analyze the inequality in CO₂ emissions, and then, they further investigated the impact of the Kyoto Protocol on the future CO₂ emissions inequality in 2010 by the same approach (Heil and Wodon, 2000). After that, Mussini and Grossi (2015) and Chen et al. (2016) further developed the decomposition methodology of the Gini index. Alcántara and Duro (2004) used the Theil index to indicate energy inequality in OECD countries. Then, Duro and Padilla (2006) extended the Theil index with Kaya factors to decompose inequality in per-capita CO₂ emissions across countries. In light of the former case studies, Remuzgo and Sarabia (2015) developed a factorial decomposition of the Theil index based on Kaya factors to study international inequality in CO₂ emissions. By integrating Theil index with Kaya factors, it opens a path toward analyzing structural inequality effect on environmental inequality. However, this approach can not compare the contributions of size effect, structural effect, and inequality effect on environmental inequality simultaneously, which to some extent covers up important information. This paper attempts to fill the gap by devising a developed-Kaya identity, which based on the pollution economy inequality index (PE index), to

decompose environmental inequality changes into economic size effect, economic inequality effect, economic structure inequality effect, technology inequality effect, and population size effect. After that, we integrate the Kaya identity with the Logarithmic Mean Divisia Index method (LMDI) to analyze contributions of each driving factor on the increment of IPI. To the best of our knowledge, this is the first time a study has aimed to associate China's environmental inequality issue with the T-shaped spatial development strategy and explain the impact of economic size, economic inequality, and economic structural inequality on environmental inequality simultaneously.

It should be noted that inequalities are natural results of progress (Deaton, 2013). For development-induced gaps, it is not about restricting the progress of those taking the lead but about accelerating the progress of those catching up. We argue that inequality does not always have to be addressed. It depends on the phases of development and the speed of catching up. Slowly catching up or even no catching up may cause unfairness. It is the unfairness that should be addressed. The crucial part is to investigate the degree of IPI in China and trace whether it is narrowing or widening during the “new normal” phase. Regarding the aforementioned perspectives, we aim to discuss the following three questions in our present study. Is there a unique characteristic of inequality distribution of China's industrial pollution, which is highly correlated to “T-shaped” spatial development strategy in China? How does economic growth impact the speed of the “catching up” in environmental inequality? What are the driving factors and the extent of their contributions? Our findings could give a new perspective on environmental inequality research in China, and also help policymakers identify the inequality of industrial pollution and its potential determinants. It would be a vital step to foster justice and maintain sustainable and inclusive growth in the future in China.

The rest of the paper is organized as follows. The methodology and data applied in this study are presented in *Data and Methodology*. *Results and Discussion* displays the results associated with the spatiotemporal variation patterns of China's IPI and their determinants. Finally, *Conclusion and Policy Implication* presents the conclusions and recommendations for future research.

DATA AND METHODOLOGY

Data

The panel data for a set of 31 provinces and municipalities (the megacities and province have the identical administrative power in China) covering the period from 2000 to 2015 were gathered (National Bureau of Statistics of China, 2000–2015a; National Bureau of Statistics of China, 2000–2015b). We excluded Taiwan, Hong Kong, and Macau, owing to the unavailability of data. The whole country was divided into three areas according to the “T-shaped” spatial development strategy: CR, ICYR, and OR, as shown in **Figure 1**. The CR covers 12 provinces and municipalities: Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Guangxi, and Hainan; the ICYR

covers 8 provinces and municipalities: Anhui, Jiangxi, Hubei, Hunan, Chongqing, Sichuan, Guizhou, and Yunnan; and the OR covers 11 provinces: Shanxi, Inner Mongolia, Jilin, Heilongjiang, Henan, Tibet, Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang.

Data on discharges of industrial wastewater (IWW), sulfur dioxide (IWG_{SO_2}), and solid waste (ISW) were derived from China Statistical Yearbook and China Statistical Yearbook on Environment (National Bureau of Statistics of China, 2000–2015a; National Bureau of Statistics of China, 2000–2015b). Population, GDP, Gross Industrial Production, and other socioeconomic factors are collected from the China Statistical Yearbook (National Bureau of Statistics of China, 2000–2015a). All economic data in this study were converted using constant prices of the year 2000 to eliminate the impact of inflation.

Methods for Measuring Inequality—Theil Index

Proposed by Theil (1967) to study the income gap between countries, the Theil index is a log-likelihood ratio statistic that is based on the concept of entropy (Kullback, 1959). Its general expression is:

$$T = \sum_{i=1}^n p_i \ln \frac{\bar{c}}{c_i} \quad (1)$$

where c_i represents per capita emissions of region i ; p_i is the population proportion of region i ; and \bar{c} is the average value of emissions.

In our study, T_{ICYR} , T_{CR} , and T_{OR} represent the Theil index of environmental inequality in the CR, ICYR, and OR, respectively, based on Eqs. 2–4:

$$T_{CR} = \sum_{i=1}^n \frac{P_i}{P_{CR}} \ln \left(\frac{P_i/P_{CR}}{G_i/G_{CR}} \right) \quad (2)$$

$$T_{ICYR} = \sum_{i=1}^n \frac{P_i}{P_{ICYR}} \ln \left(\frac{P_i/P_{ICYR}}{G_i/G_{ICYR}} \right) \quad (3)$$

$$T_{OR} = \sum_{i=1}^n \frac{P_i}{P_{OR}} \ln \left(\frac{P_i/P_{OR}}{G_i/G_{OR}} \right) \quad (4)$$

The Theil index between regions is:

$$T_{B/CR} = \frac{P_{CR}}{P} \ln \left(\frac{P_{CR}/P}{G_{CR}/G} \right) \quad (5)$$

$$T_{B/ICYR} = \frac{P_{ICYR}}{P} \ln \left(\frac{P_{ICYR}/P}{G_{ICYR}/G} \right) \quad (6)$$

$$T_{B/OR} = \frac{P_{OR}}{P} \ln \left(\frac{P_{OR}/P}{G_{OR}/G} \right) \quad (7)$$

$$T_B = \frac{P_{CR}}{P} \ln \left(\frac{P_{CR}/P}{G_{CR}/G} \right) + \frac{P_{ICYR}}{P} \ln \left(\frac{P_{ICYR}/P}{G_{ICYR}/G} \right) + \frac{P_{OR}}{P} \ln \left(\frac{P_{OR}/P}{G_{OR}/G} \right) \quad (8)$$

And the Theil index within regions is:

$$T_{W/CR} = \frac{P_{CR}}{P} T_{CR} \quad (9)$$

$$T_{W/ICYR} = \frac{P_{ICYR}}{P} T_{ICYR} \quad (10)$$

$$T_{W/OR} = \frac{P_{OR}}{P} T_{OR} \quad (11)$$

$$T_W = \frac{P_{CR}}{P} T_{CR} + \frac{P_{ICYR}}{P} T_{ICYR} + \frac{P_{OR}}{P} T_{OR} \quad (12)$$

Thus, the total Theil index can be expressed as:

$$T = T_B + T_W \quad (13)$$

Among them, T is the total Theil index. A larger Theil index indicates a greater departure from equality. T_B is the Theil index between regions, indicating that a share of total Theil index comes from the difference between regions. T_W is the Theil index within regions, indicating that a share of the total Theil index comes from the difference within regions. G is the national gross industrial production and P is the national industrial pollutant emissions. P_i represents the industrial pollutant emissions of i province; G_i represents the gross industrial production of i province; i represents 31 provinces and municipalities in China (except Hong Kong, Taiwan, and Macau due to the lack of data), where $i = 1, 2, 3, \dots, 31$. $T_{B/CR}$, $T_{B/ICYR}$, and $T_{B/OR}$ represent the Theil index between regions for the CR, ICYR, and OR, respectively. They demonstrate an advantage or disadvantage for the respective region as compared to the national average level through a minus or plus sign. If the sign of the index is plus, it indicates that the industrial pollution performance in this region is worse than the national average, and vice versa. Their value suggests the extent of inequality. $T_{W/CR}$, $T_{W/ICYR}$, and $T_{W/OR}$ represent the Theil index within the region for the CR, ICYR, and OR respectively. A greater value indicates a greater inequality within the region itself.

Methods for Analysis of the Driving Factors of Environmental Inequity—Kaya-LMDI

Inherited from the IPAT model, the Index Decomposition Analysis (IDA) is based on the index number theory for decomposition analysis. It is a simple and flexible method that needs less data and can be used to interpret spatial and temporal data. As one of the IDA approaches, the LMDI was created by Ang (2005) and is widely used to calculate contributions of relative factors to the changes in emissions because of its advantage of perfect decomposition without an unexplained residual term. In our study, we develop a simple and systematic analytical framework, within which the developed-Kaya-LMDI is combined with the environmental inequality index to investigate the factors impacting the changes of environmental inequality. Considering that the disparity of the Theil index of the regions is too little to be decomposed, the PE index is selected as a proxy variable of environmental inequality, which has a strong correlation with the Theil index (shown in *Driving Forces of Pollution Economy Inequality*).

This study decomposed IPI into five factors: population size effect, economic inequality effect, economic structure inequality effect, backward of technology inequality effect, and negative economic size effect, the identity of which is given as in Eq. 14.

TABLE 1 | Definitions of various variables in Eqs. 14–20.

Variable	Definition
p_i	$p_i = \frac{Pop_i}{Pop}$ is the ratio of the population of province i to the total population
i_i	$i_i = \frac{G_i/G}{Pop_i/Pop}$ is the per capita GDP inequality of province i . If i_i is higher than 1, it means that it is higher than the average per capita GDP of the nation
s_i	$s_i = \frac{I_i/I}{G_i/G}$ is the structure inequality of i province. If s_i is higher than 1, it means that the proportion of gross industrial production in GDP of province i is higher than the average of the nation
t_i	$t_i = \frac{Pol_i/Pol}{I_i/I}$ is the ratio of IPI of i province. If t_i is higher than 1, it means that the industrial pollution emission per unit of gross industrial production value of i province is higher than the average of the nation
a_i	$a_i = \frac{1}{G_i/G}$ is the reciprocal of the ratio of GDP of i province to national GDP. It is an inverse indicator in our model
ΔPE_{tot}	Pollution Economy inequality effect, representing the change of the inequality for industrial pollution emission along with per unit of GDP
ΔPE_p	Population size effect, representing the change of pollution economy inequality due to the change of population coefficient
ΔPE_i	Economic inequality effect, representing the change of pollution economy inequality due to the change of per capita GDP inequality coefficient
ΔPE_s	Economic structure inequality effect, representing the change of pollution economy inequality due to the change of the ratio of structure inequality coefficient
ΔPE_t	Backward of technology inequality effect, representing the change of pollution economy inequality due to the change of the inequality for industrial pollution emission per unit of gross industrial production value coefficient
ΔPE_a	Negative economic size effect, representing the change of pollution economy inequality due to the change of the reciprocal of the ratio of GDP of i province to national GDP.
PE^t	Pollution-economy index of the target year
PE^0	Pollution-economy index of the base year

TABLE 2 | Results of Pearson correlations test.

		Theil index	PE index
Theil index	Pearson correlation	1	.730 ^a
	Sig. (2-tailed)		.000
	N	124	124

^ameans the results are significant at the 1% level.

Sig. (2-tailed) indicates the significance level of the correlation in the two-tailed test.

N donates the number of variables.

$$\begin{aligned}
 PE &= \frac{Pol_i/Pol}{G_i/G} \\
 &= \sum_{i=1}^n \frac{Pop_i}{Pop} \times \frac{G_i/G}{Pop_i/Pop} \times \frac{I_i/I}{G_i/G} \times \frac{Pol_i/Pol}{I_i/I} \times \frac{1}{G_i/G} \\
 &= \sum_{i=1}^n p_i \times i_i \times s_i \times t_i \times a_i \tag{14}
 \end{aligned}$$

In the scheme of additive decomposition, the difference of the PE index could be decomposed into the above-mentioned five effects. The calculation of each effect is represented by the following equations:

$$\Delta PE_{tot} = PE_t - PE_0 = \Delta PE_p + \Delta PE_i + \Delta PE_s + \Delta PE_t + \Delta PE_a \tag{15}$$

$$\Delta PE_p = \sum L(PE_{it}, PE_{i0}) \times Ln\left(\frac{p_{it}}{p_{i0}}\right) \tag{16}$$

$$\Delta PE_i = \sum L(PE_{it}, PE_{i0}) \times Ln\left(\frac{i_{it}}{i_{i0}}\right) \tag{17}$$

$$\Delta PE_s = \sum L(PE_{it}, PE_{i0}) \times Ln\left(\frac{s_{it}}{s_{i0}}\right) \tag{18}$$

$$\Delta PE_t = \sum L(PE_{it}, PE_{i0}) \times Ln\left(\frac{t_{it}}{t_{i0}}\right) \tag{19}$$

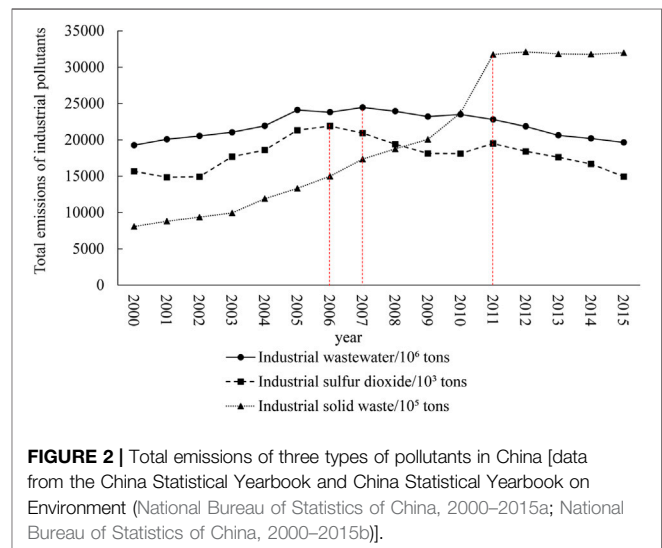


FIGURE 2 | Total emissions of three types of pollutants in China [data from the China Statistical Yearbook and China Statistical Yearbook on Environment (National Bureau of Statistics of China, 2000–2015a; National Bureau of Statistics of China, 2000–2015b)].

$$\Delta PE_a = \sum L(PE_{it}, PE_{i0}) \times Ln\left(\frac{a_{it}}{a_{i0}}\right) \tag{20}$$

where $L(x, y) = \frac{x-y}{Ln(x/y)}$, x and y are variables of the above equations correspondingly. Variables used in the models are defined in Table 1.

RESULTS AND DISCUSSION

Trends in Industrial Pollution Emissions

To understand the trends observed in industrial pollution emissions, Figure 2 shows the development trends of total

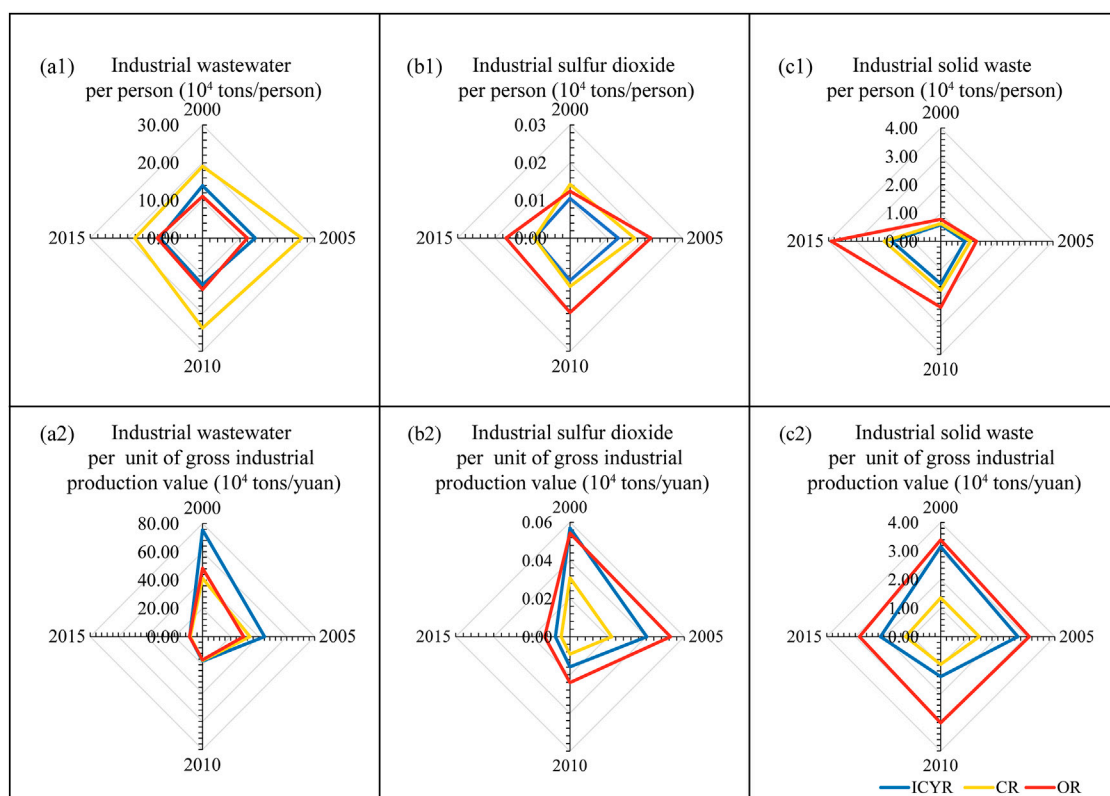


FIGURE 3 | Ratio of industrial pollution emissions to population/gross industrial production value in the Coastal Region (CR), Inland Corridor along Yangtze River (ICYR), and Other Regions (OR). **(a1)** Industrial wastewater per person (10^4 tons/person), **(a2)** Industrial wastewater per unit of gross industrial production value (10^4 tons/yuan), **(b1)** Industrial sulfur dioxide per person (10^4 tons/person), **(b2)** Industrial sulfur dioxide per unit of gross industrial production value (10^4 tons/yuan), **(c1)** Industrial solid waste per person (10^4 tons/person), and **(c2)** Industrial solid waste per unit of gross industrial production value (10^4 tons/yuan).

emissions of IWW, IWG_{SO_2} , and ISW from 2000 to 2015. The results demonstrate that China's IWW and IWG_{SO_2} have both experienced a significant initial increase and a later decrease. The two lines on the graph also manifest the turning points in 2006 and 2007, respectively. However, ISW had a consistent increase from 2000 to 2011 and stabilized after that.

To identify how these pollution burdens have been allocated in regions, industrial pollution emissions based on the population and gross industrial production value are divided into CR, ICYR, and OR, as shown in **Figure 3**. We find slight differences in the ranks of regions regarding economy and population. For IWW, CR had the highest per capita IWW (see **Figure 3 (a1)**), while ICYR had the highest IWW emission intensity (the ratio of IWW and gross industrial production). It was also found that there was a downturn trend between 2000 and 2015, for 0.97×10^4 /person reduction (5.10%) in CR and 66.32×10^4 /yuan reduction (87.93%) in ICYR. Emissions of IWG_{SO_2} and ISW in OR are the highest among the three regions, regardless of emissions per capita or per unit industrial output. It is notable that the gap between CR and ICYR is shrinking, while it is widening between OR and the former two regions.

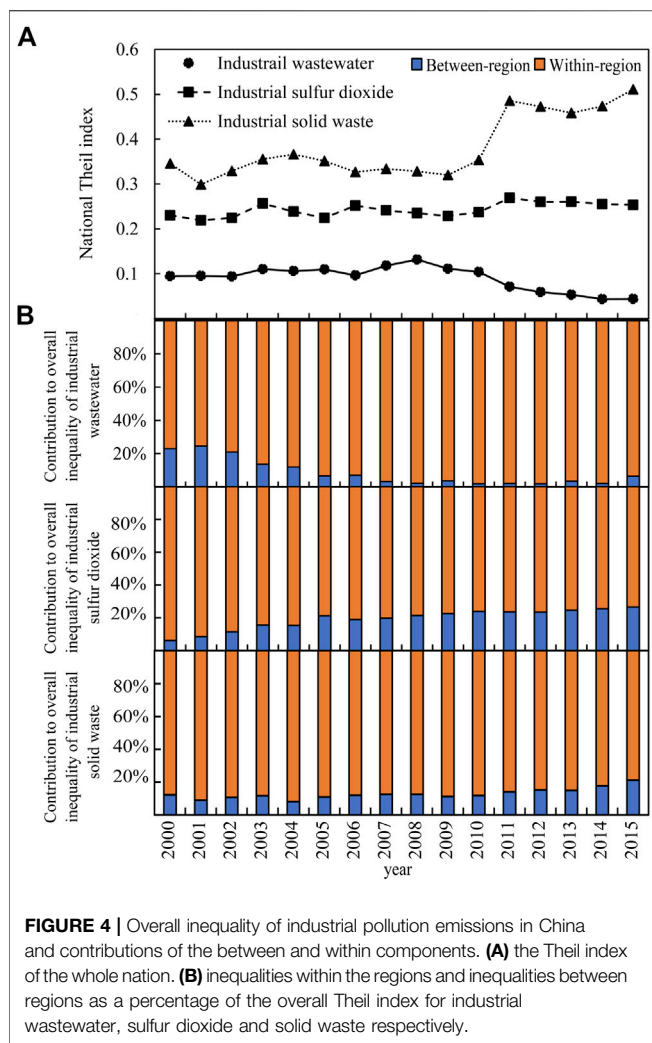
Consequently, the questions are whether these gaps arise from inequality within or between the regions, and whether

the results vary in terms of different types of industrial pollutants.

Theil Index of Industrial Pollution Emissions

As mentioned previously, there are many indicators to measure IPI. In this study, we select the Theil index to conduct the analysis because of its decomposability regarding the between and within components. As can be observed in **Figure 4A**, the inequality of ISW stands out as the pollutant with the highest Theil index, implying that it is still a challenging task for China to reduce solid waste pollution during the industrialization process. In contrast, the lowest Theil index over the period can be found for IWW. This could be partially explained by the fact that the water pollution-intensive industry is more sensitive to legal policy instruments than the rest of the industries (Zheng and Shi, 2017).

Further decomposition of the Theil index of China's industrial pollution suggests that the overall inequalities of IWW, IWG_{SO_2} , and ISW are predominantly contributed by inequalities within the regions (**Figure 4B**). Inequalities within the regions contribute an average of 91.33% to IWW, 78.51% to IWG_{SO_2} , and 70.20% to ISW from 2000 to 2015. This



indicate that inequality of industrial wastewater has relatively small differences between regions, while the differences between regions contribute more to industrial sulfur dioxide inequality and industrial solid waste inequality. The difference is due to the production characteristics of different types of industrial pollutants. Although inequalities between regions have accounted to a lower extent for the overall inequalities, this does not lessen the significance of discussing them because inequalities between regions tend to reflect the changes and levels of the overall inequality (Galbraith and Choi, 2020). Thus, we further analyze the between and within components of Theil indexes in CR, ICYR, and OR to obtain a precise understanding of regional inequality performance.

In **Figure 5**, the Theil index between regions (T_B) illustrates the advantaged or disadvantaged situation of a region as compared to the national average level (that approaches 0). The Theil index within regions (T_W) indicates the inequality degree among provinces within the region itself. As we can see, the yellow symbols (representing the CR) show lower T_B , with an average of -0.026 for IWW (**Figure 5 (a1)**), -0.152 for IWG_{SO_2} (**Figure 5 (b1)**), and -0.155 for ISW (**Figure 5 (c1)**),

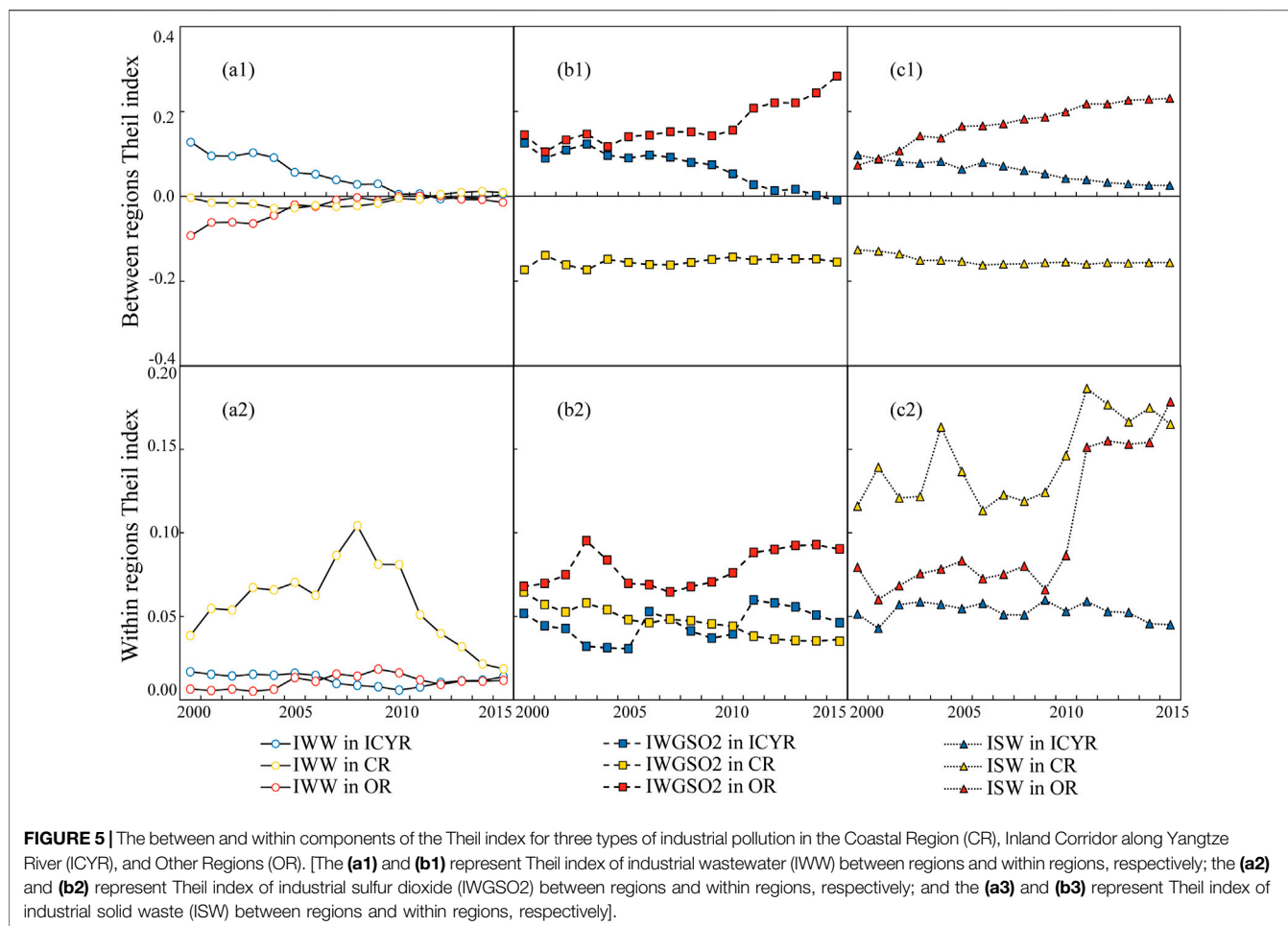
whereas higher T_W , with an average of 0.058 for IWW (**Figure 5 (a2)**), 0.046 for IWG_{SO_2} (**Figure 5 (b2)**), and 0.143 for ISW (**Figure 5 (c2)**). Inequality is indeed a natural result of economic and social progress. However, it will not reduce or disappear by itself due to development. In the case of CR, even if the region's inequality is diminishing as a whole, sub-level inequalities are quite severe within the region. It is crucial for the government to address inequalities both between and within regions if necessary. As expected, this contradiction is solvable. In the present study, we find that the inequality within CR has generally decreased in the later period (from 0.104 in 2008 to 0.019 in 2015 for IWW, 0.048 in 2007 to 0.036 in 2015 for IWG_{SO_2} , and 0.186 in 2011 to 0.165 in 2015 for ISW).

The phase characterized by low inequality between regions and high inequality within the region is not a necessary developing phase. In the case of ICYR, we see a downward trend in inequality between regions and equality on average within regions, for all types of industrial pollution. Even though, as a representative of the drainage economy, the ICYR showed a disadvantage regarding IWW emissions compared to the rest of the regions (**Figure 5 (a1)**) in the early stage (0.128 of T_B in 2000), the trend converged to the national average level afterward (0.006 of T_B in 2015). ICYR's performance displays the potential to balance environmental outcomes with economic outcomes and achieve better equality due to the advantage of late-development.

This disadvantaged situation is especially detrimental for regions that lack both development opportunities (or capacity) and government assistance. As shown in **Figure 5**, inequalities are increasing in the OR, both between and within regions. Furthermore, the two-fold disadvantages are exacerbating the situation. By 2015, the T_B increased to 0.012 , 0.157 , and 0.138 for IWW, IWG_{SO_2} , and ISW, respectively. Simultaneously, the T_W increased to 0.005 , 0.022 , and 0.099 for IWW, IWG_{SO_2} , and ISW, respectively.

The findings in **Figure 5** show that there is significant heterogeneity in the regional differences and development trends of different types of industrial pollutants. Due to the significant differences in the production processes and end-of-pipe treatment methods of IWW, IWG_{SO_2} , and ISW, there will be time sequential differences in the time required for the promotion of different categories of pollutant treatment technologies and the emergence of related environmental treatment effectiveness. It is important to note that in the process of rapid development, if pollution control technologies are not effectively upgraded in a timely manner, it will lead to the accumulation of industrial pollutants in the natural environment, which may exceed environmental capacity and then lead to serious environmental pollution incidents. China needs to pay particular attention to the potential environmental risks associated with ISW generation and disposal in OR.

The results above tell us that IPI plays out differently among different regions. We assume that "structural force," which is one of the efficient means of the visible hand of government, is a predominant driver that impacts the



geographic allocation of economic benefit and environmental burden. Accordingly, we verify it from the spatial and temporal perspectives.

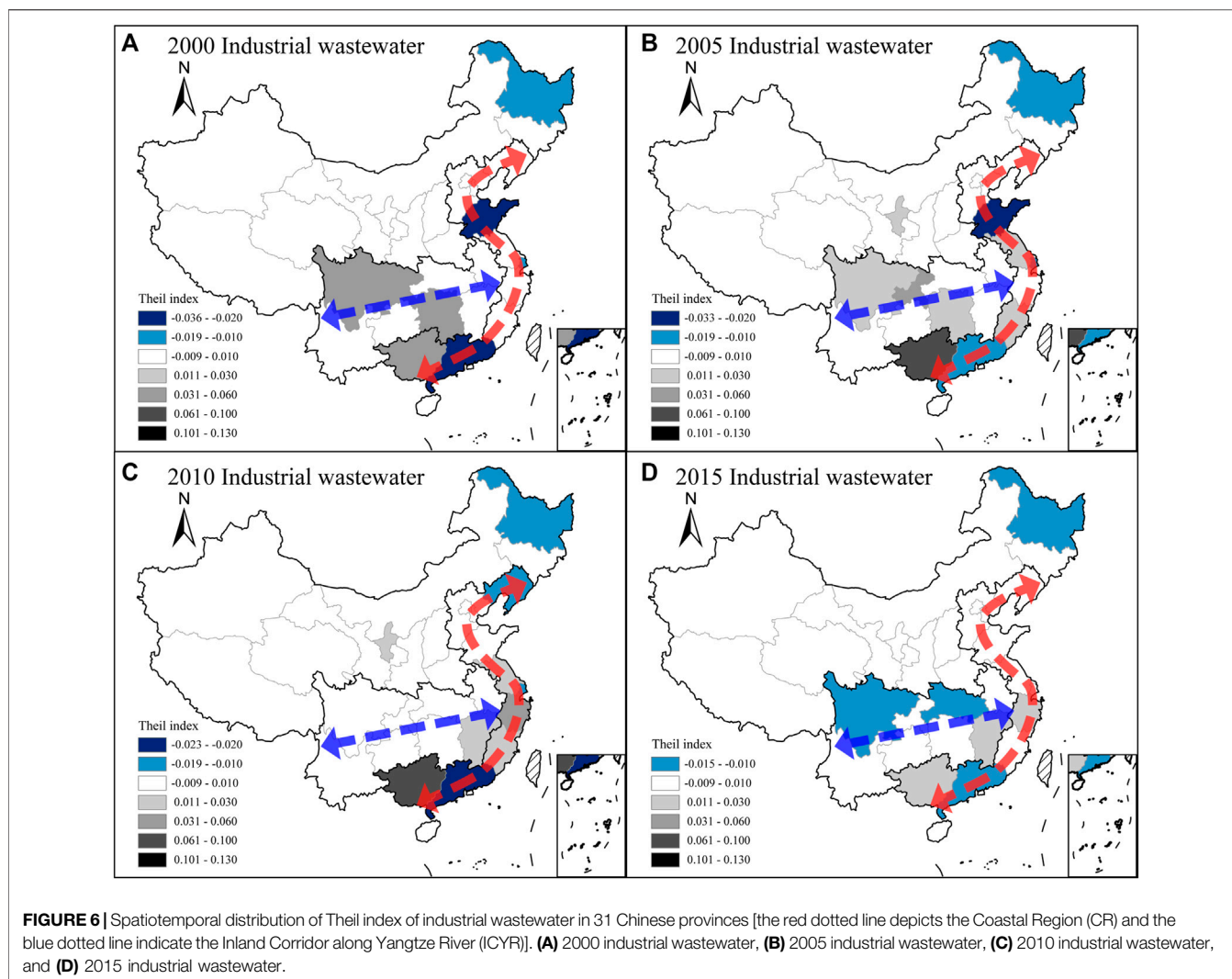
Spatiotemporal Distribution of IPI

To test our assumption, we depict the spatiotemporal distributions of IPI based on the magnitude of the Theil index (see Figures 6–8). The darker gray zone represents the provinces with relatively worse environmental-economic performance. The darker blue, red, and brown colors represent the provinces that are relatively better off and the white color signifies that the performance converges to the national average.

The spatial and temporal distribution of environmental equality varies across industrial pollutant emissions. The Theil index measured for IWW in most provinces converges to -0.009 – 0.010 (white patch area in Figure 6) in 2015, which indicates that the influence of advantages and weaknesses between provinces is fading gradually and the equality has begun to exhibit an upward trend. In contrast, provincial gaps are widening in terms of IWGSO₂ (Figure 7) and ISW (Figure 8). Water pollution-intensive industry is probably more sensitive to legal policy instruments than the rest of the industries (Zheng and Shi, 2017); meanwhile, Chinese government has made a great effort to promote the nationwide battle to prevent and control

pollution (The CPC Central Committee and the State Council, 2021). In particular, these gaps are generated by the slow pace of those catching up rather than those taking the lead at a fast pace. Specifically, the lowest Theil index of IWGSO₂ and ISW have been steady from 2000 to 2015. The Theil index of IWGSO₂ of Guangdong province is constantly the lowest in the whole of China and was -0.037 in 2000 and -0.035 in 2015. The lowest value of the Theil index of ISW appears in Jiangsu province, whose value was -0.036 in 2000 and -0.035 in 2015, whereas, Shanxi province showed the highest Theil index of IWGSO₂, which was 0.066 in 2000 and which rose to 0.081 in 2015, with a growth rate of 23%. Simultaneously, Shanxi province also has the highest Theil index of ISW that rose from 0.157 in 2000 to 0.187 in 2015.

The “structural features” hypothesis for China is verified in our study. The “T-shaped” spatial development strategy strongly affected the performance of IPI. Indeed, a similar “T-shaped” geographic distribution of CO₂ emissions and industrial pollution emissions can be found in previous studies (Wang and Liu, 2017; Zhang et al., 2018b; Guan et al., 2019; Liu et al., 2020). Our study highlights the inequality degree of industrial pollution and the “T-shaped” geographic distribution characteristic becomes more evident. As can be seen, from the spatial perspective, the CR axis of the “T-shaped” strategy, which is



the first developed region in China after the reform and opening up of the economy, accounts for the majority of colored patches in **Figures 6–8**. The provinces situated in this region have had a significant advantage of industrial pollutant reduction and economic development over the rest of China. From the temporal perspective, the ICYR axis of the “T-shaped” strategy is the only region that has shown a consistent growth of equality for all industrial pollution types from 2000 to 2015 (fewer black patches over time). Moreover, a notable upward trend (more colored patches) is observed during the 12th Five-Year Plan Period (2011–2015). It is exactly in this period that China enforced a national strategy to develop the Yangtze River economic belt, which was followed by a remarkable outburst of economic development and sterner pollution restrictions.

However, in the provinces located in regions that are not supported by the national territorial space planning strategy (OR), industrial pollution inequalities are deteriorating, especially regarding the IWG_{SO_2} and ISW. Thus, in **Figures 6–8**, more provinces in the OR have been observed to be gray and dark gray over time.

We argue that the development-induced gaps between provinces are inevitable. Nevertheless, more provinces are catching up with regards to progress, especially those provinces located in the ICYR. However, it should be noted that less-developed provinces in the OR have been struggling in a disadvantageous position and the gap is still widening. Consequently, these provinces will be incapable of catching up with their counterparts without the counter-measures that arise from “structural forces.”

Earlier studies have shown similar results. Berthe and Elie (2015) argued that government interventions are a prerequisite for addressing inequality issues in environmental problems. Wang et al. (2018) suggested that the improvement of industrial structure to reduce pollution emissions could only be achieved by a unified and strict legal market environment in China. Zhang et al. (2018a) proposed that stricter environmental regulations should be implemented to induce a structural break in the industry and curb the associated emissions. We have confirmed these arguments through our study of China's IPI. Attention should be paid to remedying the weakness of less-developed regions and empowering them to

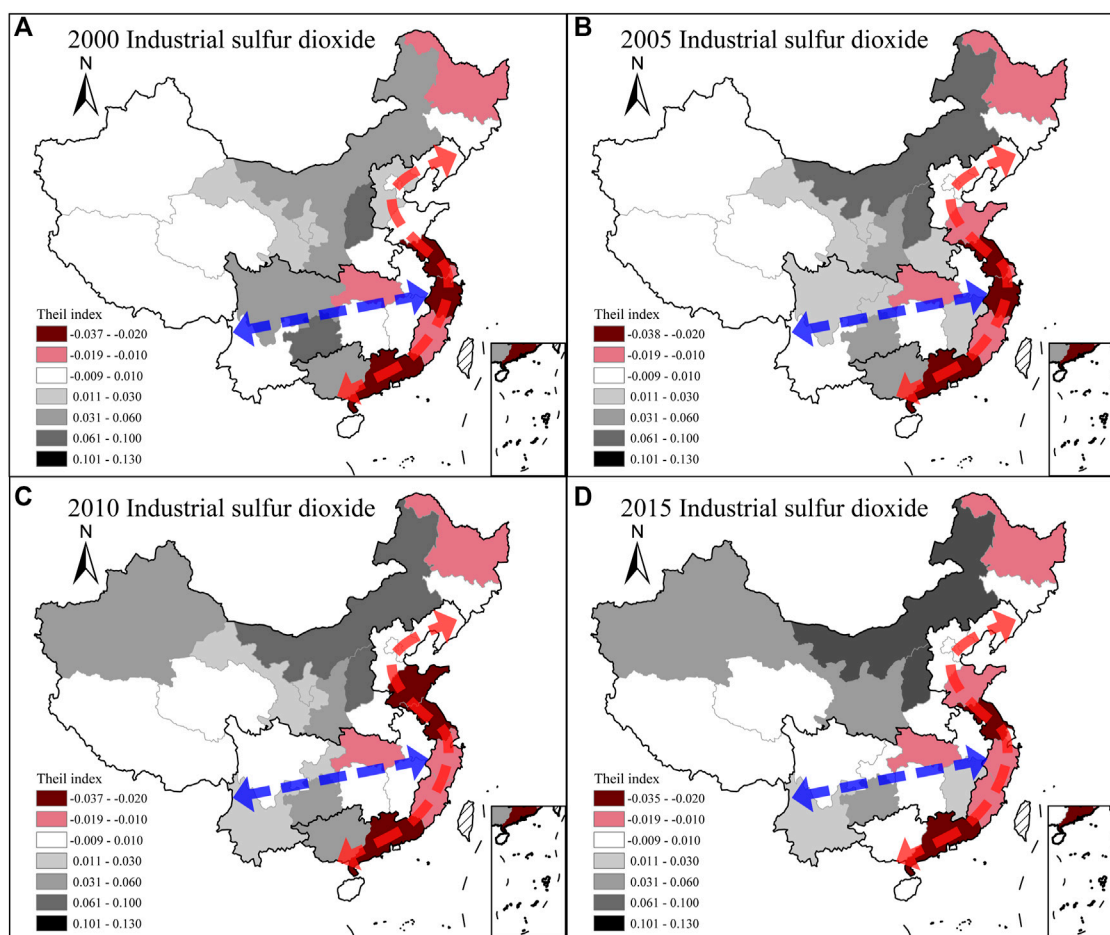


FIGURE 7 | Spatiotemporal distribution of Theil index of industrial sulfur dioxide in 31 Chinese provinces [the red dotted line depicts the Coastal Region (CR) and the blue dotted line indicate the Inland Corridor along Yangtze River (ICYR)]. (A) 2000 industrial sulfur dioxide, (B) 2005 industrial sulfur dioxide, (C) 2010 industrial sulfur dioxide, and (D) 2015 industrial sulfur dioxide.

achieve green development by taking advantage of the latecomers, as in the case of ICYR.

Driving Forces of Pollution Economy Inequality

To go deeper into the impact on “structural spatial-temporal distribution features” of China’s IPI, we decomposed the inequality into five effects: population size (ΔPE_p), economic inequality (ΔPE_i), economic structural inequality (ΔPE_s), technological inequality (ΔPE_t), and economic size (ΔPE_a). As mentioned previously, the disparity of the log-likelihood ratio Theil index is too little to be decomposed; thus, PE index, as a proxy of the Theil index, was used to implement the calculation of Kaya-LMDI. First, we ran a correlation test of the two indexes to verify the consistency, as shown in **Table 2**. The correlations are significant at the 1% level.

The weights of each factors’ effect are shown in **Figure 9**. The pollution economy efficiency in CR is generally higher than the national average (with PE index lower than 1), implying that CR has a great edge in environmental equality.

The technological inequality effect contributes most to the PE changes in 2000–2005 for all pollutants: 15.10% for IWW, 8.17% for IWG_{SO_2} , and 6.59% for ISW. However, the economic inequality effect plays a more critical role in the changes of inequality in CR in the later periods, except for ISW in the period 2005–2010.

From **Figure 9**, a clear downward trend in inequality in ICYR can be observed for industrial pollutants from 2000 to 2015, except for IWW in the period 2010–2015. The PE index for all types of industrial pollution is converging to 1. This implies that ICYR is catching up in the progress of economic-environmental balance and reaching the national average after years of effort. The predominant contributors vary in terms of different types of industrial pollutants and different periods. For IWW, the ΔPE_t chiefly caused the decrease in 2000–2010; however, effects of the economic inequality factor and the economic structure inequality factor stand out and contributed most to the changes: 6.75% from ΔPE_i and 5.19% from ΔPE_s in 2010–2015. Concerning IWG_{SO_2} and ISW, ΔPE_t has been the main contributor over the study period. Meanwhile, ΔPE_i and ΔPE_s have influenced these two items to some extent.

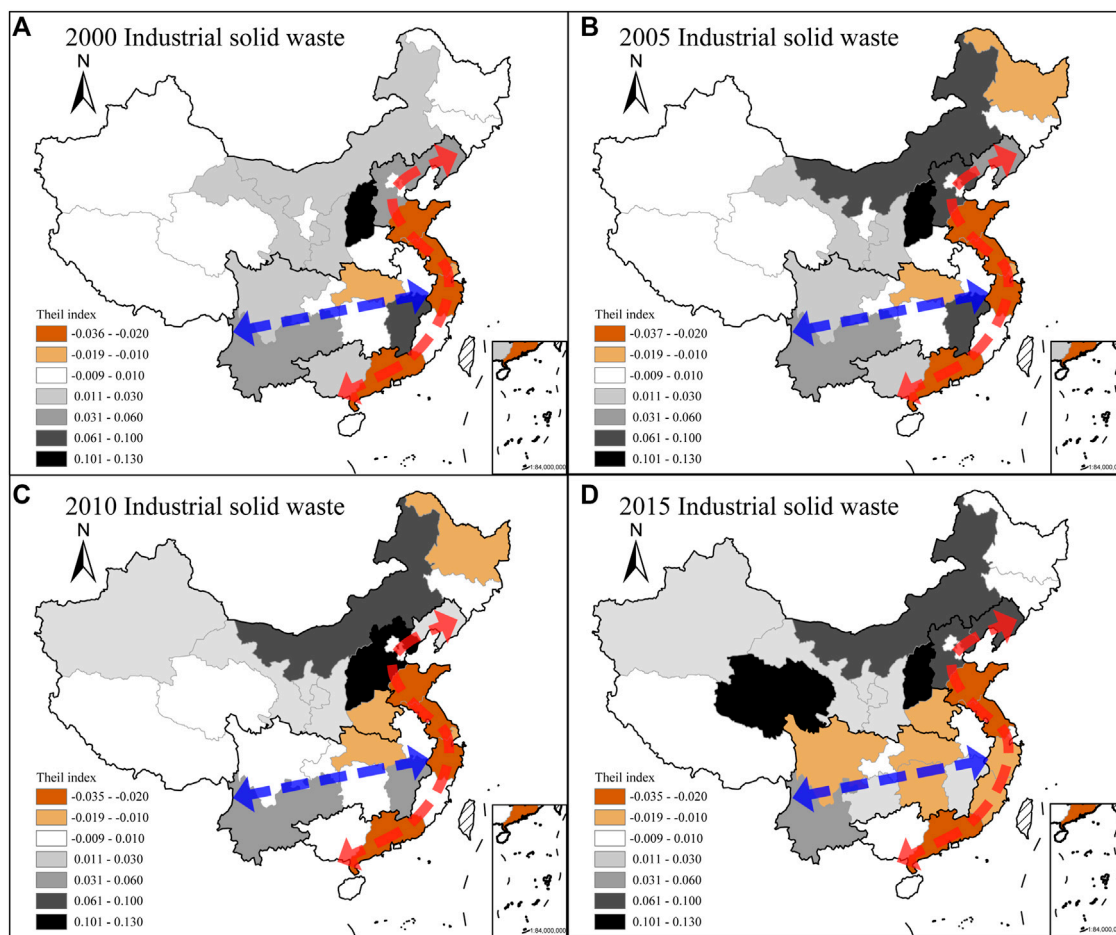


FIGURE 8 | Spatiotemporal distribution of Theil index of industrial solid waste in 31 Chinese provinces [the red dotted line depicts the Coastal Region (CR) and the blue dotted line indicate the Inland Corridor along Yangtze River (ICYR)]. **(A)** 2000 industrial solid waste, **(B)** 2005 industrial solid waste, **(C)** 2010 industrial solid waste, and **(D)** 2015 industrial solid waste.

In the case of the OR, remarkable disadvantages in environmental inequality are observed regarding IWG_{SO_2} and ISW. Moreover, both show increasing divergences from the national average over time. Further, we can observe that the technological inequality effect has always been the main contributor to the increments of IWG_{SO_2} and ISW over the study period.

The findings above show that the technological inequality effect is more likely to determine the performance of environmental inequality in pre-development phases or less-developed regions. Improvement of technology is the key strategy to reduce industrial pollution emissions, especially for the regions' initial developing stages. Furthermore, it is interesting to find that when technologies are markedly promoted, the economic structure inequality factor, together with the economic inequality factor, rises and principally drives environmental inequality changes in the transition period. Following this, economic inequality effect will probably determine the performance of environmental inequality. For instance, in **Figure 9**, effects of ΔPE_i and ΔPE_s in CR and ICYR are substantially higher than those in OR. Moreover, ΔPE_i and ΔPE_s outweigh ΔPE_t for all industrial pollutants in CR in the 11th 5-year plan period (2005–2010) and for the IWW in

ICYR in the 12th 5-year plan period (2010–2015). The ΔPE_i outweighs other factors for all types of industrial pollutants in CR in the 12th 5-year plan period (2010–2015).

Finally, economic inequality appears to be a better indicator to interpret the changes in environmental inequality in relatively developed phases. The economic size is the better indicator to construe the evolution of environmental inequality in pre-development phases. **Figure 9** proves this as the $|\Delta PE_a|$ outweighs $|\Delta PE_i|$ in the 10th 5-year plan period (2000–2005). By comparison, $|\Delta PE_i|$ is much higher than $|\Delta PE_a|$ in the period of the 11th and 12th 5-year plans (2005–2015).

CONCLUSION AND POLICY IMPLICATION

In this study, features of IPI in China were studied from several perspectives, such as, the degree of inequality, the spatial variation, and the determining drivers.

First, as indicated by the Theil index, the burden of IWW is the most equally shared, while ISW showed the highest inequality.

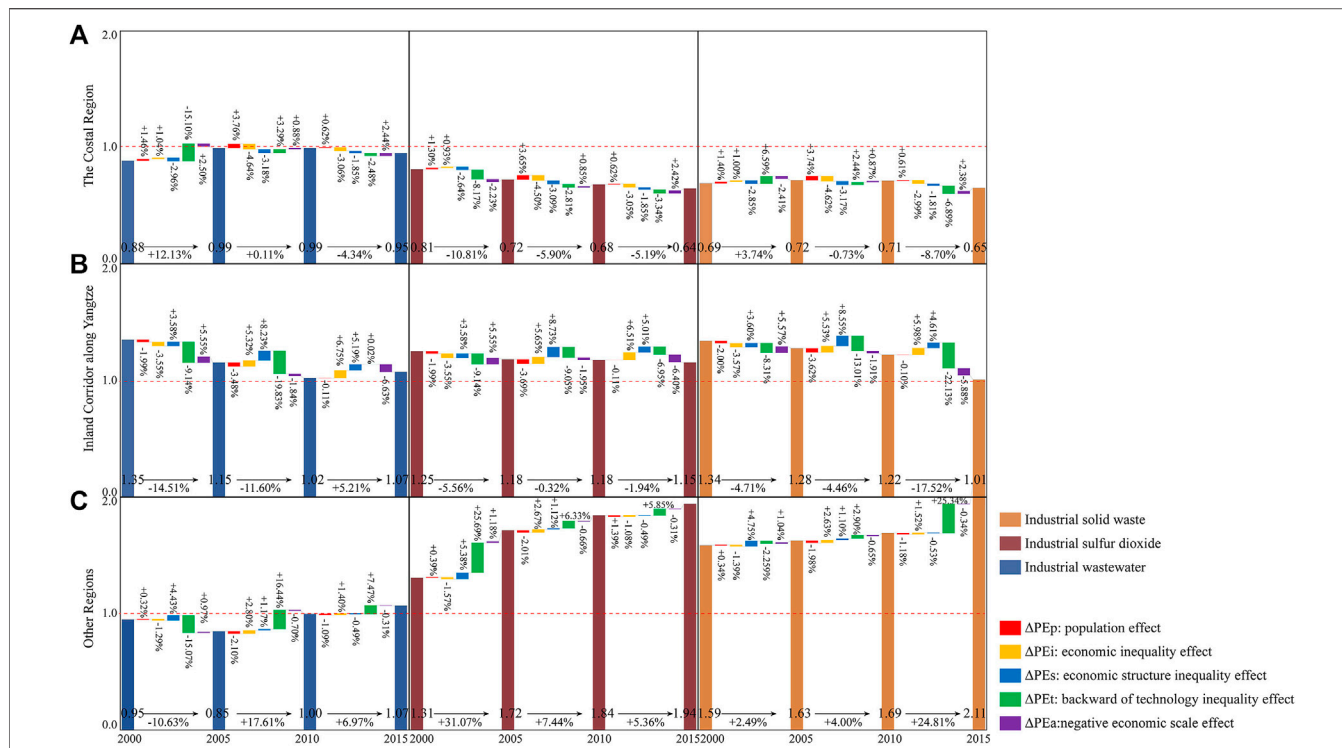


FIGURE 9 | Weights of driving factors' effect of industrial pollution inequality in China. **(A)** The coastal region, **(B)** Inland corridor along Yangtze, and **(C)** Other regions.

We then found that the differences within the region itself have caused inequality in all three types of industrial pollutants. In addition, heterogeneity exists due to geographic development zoning. Specifically, the speedy development in CR is accompanied by low inequality between regions but high inequality within the region. ICYR manifests the advantage of late-development to balance environmental outcomes with economic outcomes. Conversely, OR could be “pollution havens” for resource-intensive and/or pollution-intensive industries, which further aggravates the disadvantage regarding catching up to the progress of its counterparts.

Second, our study has confirmed that a “structural features” hypothesis exists in environmental inequality in China. The national territorial space planning strategy plays a significant role in the allocation of economic benefit and industrial pollution burden in the Chinese context. Inequalities in the two axes of “T-shaped” spatial development strategy—CR and ICYR—have congruously performed well with the implementation of corresponding policies in different periods. The gap between the ICYR and CR is narrowing, whereas an even greater inequality in the OR is being observed.

Third, we go deeper into the impact of driving factors on the evolution of inequality by integrating the inequality index with the LMDI method. Through this novel technique, noteworthy findings were discovered in this study. The first is that the technological effect may determine the performance of environmental inequality decisively in a less-developed phase or a less-developed region, and the economic

inequality effect together with the economic structural inequality effect would be the main determinant in the middle or transition period. Economic inequality effect would be the determinant afterward. The second is that economic inequality could be a better decomposing factor to environmental inequality in more developed districts or districts in higher developing phases, whereas the economic size is a better indicator to interpret the changes in environmental inequality in pre-development phases.

We should point out that for progress regarding environmental inequality, the suffering of provinces in OR is a necessary development stage. Still, we need to raise our guard, for the gap has widened in recent years. Based on our findings, we derived two main policy implications.

- 1) Leveraging the important role of national territorial space planning strategy in mitigating industrial pollution inequality

Based on the normative principle that everyone should share more fully and fairly the benefits of social development (The State Council Information Office of the PRC, 2019), China has implemented large-scale national programs to meet the inequality challenges, such as the Battle Against Poverty, Development of the West Regions Strategy, and so on. Among them, the launch of the national strategy “ecological conservation and high-quality development of the Yellow River Basin” in 2019, which covers 7 provinces of the OR in our study, would be a huge support in developing the OR provinces. The experiences of

provinces in the OR and ICYR have verified the possibility of balancing economic development and environmental protection. Latecomers could learn from these experiences and make an effort to catch up. Our findings show that national territorial space planning strategy plays a crucial role in the allocation of economic benefits and environmental benefits. Thus, the government should take up the responsibility to help the OR catch up and reallocate environmental-economic wellbeing more fairly to promote the nation's coordinated development. In the process of strategy implementation, stricter environmental regulation and green technologies are extremely pivotal to achieving win-win outcomes regarding environmental protection and economic growth.

- 2) Strengthen the communication, cooperation, and assistance in green technologies between developed and less developed regions

The key to reducing IPI between regions is to lower pollution emission intensity, and the root lies in the promotion of green technology. In China, with the advantage of coordinating all efforts to complete key national undertakings, green technology barriers should be broken through a comprehensive arrangement and mutual assistance. At the national level, incentives and subsidies can be used to give more financial support to OR to promote green technologies and develop green industries. At the regional level, the CR and the ICYR should take the initiative to share green technologies with OR. Together, they can help the less developed regions to give better play to their late-development advantages.

However, some scholars contend that inequalities are related to gaps in the relative size of the regions (Bruner, 2017). To prove this, further evidence is required for a more precise conclusion. A major limitation of this study is that we did not calculate hidden industrial pollution's unequal exchange along with inter-provincial trade. Undeveloped areas may face worsening

inequality of industrial pollutant emissions if the virtual emissions are accounted for. In the future, scholars could research IPI generated by trading and whether similar structural features exist within the transition of inequality in China. In addition, we have proposed a sample developed-Kaya-LMDI method, which allows us to compare the size effect, inequality effect, and structural inequality effect of economy on IPI. Along the same lines, the developed-Kaya-LMDI could be constructed to compare size effect, inequality effect, and structural inequality effect of population or other socioeconomic factors that meets other research needs.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JL: Conceptualization, Methodology, Writing-Original draft preparation, Data curation, Formal analysis, and Visualization. YW: Supervision, Conceptualization, and Writing-Review and Editing. LZ: Writing-Review and Editing. P-PJ: Writing-Review and Editing. Y-MH: Writing-Review and Editing. T-TH: Writing-Review and Editing.

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