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# Influencing effects and spatiotemporal differentiation of pollutant discharge from industrial wastewater and domestic sewage in China

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The driving forces and their spatiotemporal differences of pollutant discharge in 30 provinces in China from 2001 to 2020 were investigated by adopting the logarithmic mean division index (LMDI) method, distinguishing between industrial and domestic wastewater pollutant discharge. Our study results show that economic expansion was the dominant driver of chemical oxygen demand (COD) and  $\text{NH}_3\text{-N}$  discharge in China, mainly due to the impact of rapid economic development in the developed eastern provinces. The gap among 30 provinces in the contribution related to the driving effects of industrial COD and  $\text{NH}_3\text{-N}$  discharge greatly narrowed with time, tending toward the national average. It showed the significant effectiveness of industrial structure adjustment, clean production, and the technology of industrial wastewater treatment across the country. Industrial COD and  $\text{NH}_3\text{-N}$  discharge has been reduced to a certain extent. However, with rapid economic growth and urbanization, the domestic sewage treatment volume was still increasing, and the growth rate was faster than that of GDP in some provinces. The technology of many provinces had gradually failed to meet the growing demand for treating domestic sewage pollutants. Consequently, the influencing contributions had significant regional differences among provinces. The governance of the water environment in China should attach importance to technological advances for domestic water conservation and wastewater treatment in the future.

## KEYWORDS

COD/ $\text{NH}_3\text{-N}$  discharge, industrial and domestic pollution, influencing effects, spatiotemporal differentiation, logarithmic mean division index method

## Highlights

- The disparities of the influencing effects of industrial and domestic pollution discharge were disclosed.
- The spatiotemporal dynamics of the influencing effects of wastewater pollution discharge were investigated in China.
- The gap among 30 provinces in China in each effect's contribution to industrial COD and  $\text{NH}_3\text{-N}$  discharge was narrowing.
- A large gap remained among 30 provinces in China in each effect of domestic COD and  $\text{NH}_3\text{-N}$  discharge.

# 1 Introduction

As economic development in China has entered a new normal, the development emphasis has shifted from pursuing speed to quality. The goal of improving the ecological environment has become an important element of high-quality development. Environmental pollution is still serious in China; water pollution incidents have occurred frequently, causing a constant water environmental crisis. Because of this, the governments have undertaken measures to improve the water environment (Cheng et al., 2022; Jin et al., 2014; Li et al., 2022). However, it is still insufficient in terms of the condition of rapid economic development (Liu et al., 2021; Xie et al., 2022; Yao et al., 2019). In recent years, some positive outcomes have emerged, and the volume of industrial wastewater discharge has decreased considerably in China. In contrast, domestic sewage discharge has continued to increase with rapid urbanization. In addition, significant differences between the changes of domestic and industrial pollutant discharge were found in terms of chemical oxygen demand (COD) and ammonia nitrogen ( $\text{NH}_3\text{-N}$ ). At the end of the 11th 5-year plan (2006–2010), the discharge of domestic COD and  $\text{NH}_3\text{-N}$  was 1.8× and 3× the discharge of industrial COD and  $\text{NH}_3\text{-N}$  (ChinaNBoSo, 2020). By the 13th 5-year plan (2016–2020), the ratios of domestic to industrial COD and  $\text{NH}_3\text{-N}$  discharge increased to 6.7 and 3.2 (ChinaNBoSo, 2020). Accordingly, it is necessary to understand the driving mechanisms of the changes in water pollutant discharge in the economic transitional period in China.

China's environmental pollution and economic growth nexus has received increasing attention in recent years and has emerged as an important topic among economists and policymakers. The most common argument in the theoretical research is that the environmental Kuznets curve (EKC) hypothesis holds that the levels of pollution first increase with economic growth and decline subsequently relative to economic growth in higher levels (Grossman and Krueger; Panayotou, 1993; Grosman and Krueger, 1994; Shen, 2006; Li et al., 2024; Ozturk et al., 2024; Al-Mulali et al., 2015). The EKC hypothesis and its empirical study are important values in understanding the dynamic change of water environmental quality and have indicative significance (Long et al., 2019; Chen et al., 2016). However, wastewater discharge is a complex process that involves all aspects of socio-economic development (Ruan and Yan, 2022). Numerous scholars in this field have examined the key influencing factors of environmental change (Dietz and Rosa, 1997; Chen et al., 2010; Shahbaz et al., 2014; Wang and Feng, 2017). Some scholars have selected variables from economic, structure, population, and technical effects. For example, Vincent (1997) adopted population density (Vincent, 1997). Cole (2004) used trade factors (Cole, 2004). Shen (2006) selected the secondary industry share, population density, *per capita* physical capital, and labor (Shen, 2006). Lee et al. (2010) chose political system-related factors (Lee et al., 2010). Zhang et al. (2017) focused on the total population and volume of urban water consumption per GDP (25). Cai et al. (2020) selected economic growth-per-capita GDP (26).

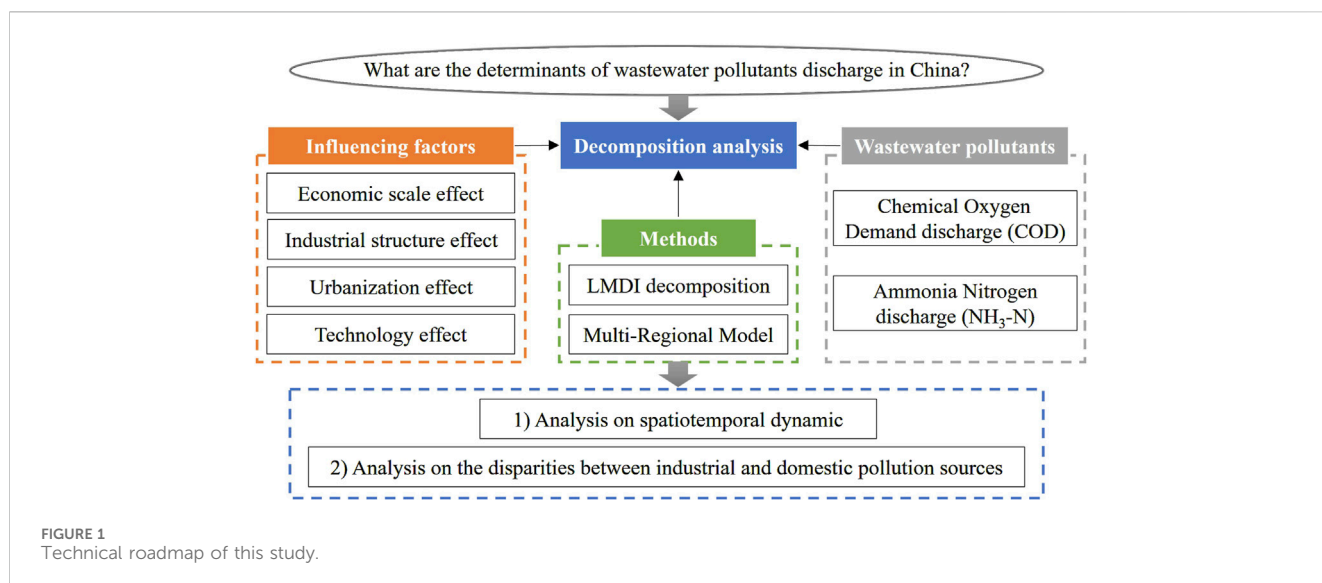
In relation to calculation methods, it is acknowledged that factor decomposition analysis has a wide range of applications in the environmental fields (Geng, 2011; Shao et al., 2014; Robaina-Alves

et al., 2016). Many scholars apply the logarithmic mean divisia index (LMDI) method to the driving influences analysis of wastewater discharge (Ang and Choi, 1997; Jeong and Kim, 2013; Xu et al., 2014; Li et al., 2019; Rasul, 2016). For example, Zhao and Chen (2014) account for the Chinese agricultural water footprint from 1990 to 2009, decomposing the driving forces into diet structure effect, efficiency effect, economic activity effect, and population effect (Zhao and Chen, 2014). Geng et al. (2014) used the LMDI method and found that economic factors made a positive contribution to the industrial wastewater discharge, whereas the technical improvement considerably offset emission increases (Geng et al., 2014). Recently, we have realized that understanding the spatial matching between social, resource, and environmental factors when improving water quality, controlling wastewater discharge, and enhancing wastewater management is a problem we should consider (An et al., 2018). Zhang et al. (2021) constructed an LMDI decomposition model to quantitatively study the spatiotemporal distribution and driving effects in urban wastewater treatment (Zhang et al., 2021). Tian et al. (2023) explored the determinants of wastewater discharge reduction and divided Mainland China into seven regions to clarify the differences among distinct regions (Tian et al., 2023).

However, the studies on wastewater discharge analyzed by the LMDI method still have some limitations. Most studies only measured the decomposition effect of the total wastewater discharge or industrial wastewater discharge but lacked an analysis of domestic sewage pollution discharge (Chen et al., 2019; Wei et al., 2019; Chang and Zhu, 2021). In addition, most research on the spatial-temporal characteristics has focused on simple descriptions instead of relevant spatial analysis (Zhang et al., 2021; Jia et al., 2017). China has a vast territory, and due to the natural environment, economic condition, technology, and other factors, different regions have distinct wastewater discharge statuses and driving factors (Yang et al., 2015). However, regional heterogeneity has usually not been elaborated in existing studies (Ma et al., 2020); nor have investigations distinguished the drivers influencing industrial and domestic pollution discharge in different provinces.

Against this background, this paper addresses these issues. It makes efforts to decompose the spatiotemporal influencing effects of regional development in COD and  $\text{NH}_3\text{-N}$  discharge in China, using the datasets at the Chinese provincial level from 2001 to 2020, which provide up-to-date information on the historic behavior of water pollution variables. The general contribution of this study is two-fold. On the one hand, the present study contributes to new knowledge by decomposing the analysis on the disparities of influencing effects of industrial and domestic pollution discharge. On the other hand, we employed the LMDI and multi-regional (M-R) model to investigate the spatiotemporal dynamic contributions of the influencing effects, which can help the government formulate more precise policies for regional wastewater discharge reduction. To the best of our knowledge, the differences in terms of industrial wastewater and domestic sewage have not been investigated. We believe that this study could open a way forward in achieving a specific viewpoint for future studies on the influence of pollution from development.

The remainder of this paper is organized as follows. The “Data and methods” section briefly describes the data and analytical



methods and models used in this study. The “Results and discussion” section presents and discusses the results. The “Conclusions and future studies” section summarizes our findings and offers some concluding remarks and further research direction.

## 2 Data and methods

The decomposition models were proposed based on LMDI methods and the M-R model to analyze the influencing factors of COD and  $\text{NH}_3\text{-N}$  discharge in China in terms of economic scale effect (ESE), urbanization effect (UE), industrial structure effect (ISE), and technology effect (TE). The analysis focused on two aspects: 1) the disparities between industrial and domestic pollution sources; 2) the spatiotemporal dynamics of the influencing effects. The technical roadmap of this study is shown in Figure 1.

### 2.1 Proposed LMDI decomposition

The LMDI model can separate each factor’s contribution to the total index and trace causes for changes in the index. It is widely applied because it has no residuals and is transparent in interpreting decomposition results (Román-Collado and Casado Ruiz, 2024; Tian et al., 2025). For this reason, it has become a commonly used approach in studying the driving factors of environmental problems.

Based on the KAYA identify, the LMDI method in this study for decomposing the influence in COD and  $\text{NH}_3\text{-N}$  discharge from economic development was constructed in the base year and target year as Equation 1.

$$V_i = \sum_j V_{ij} = \sum_j x_{i1} x_{i2} \cdots x_{ik} \quad j \in [1, k] \quad (1)$$

where  $V_i$  denotes the whole volume of regional water pollution discharge, which varies depending on  $k$  drivers.

According to the LMDI additive principle, the specific expression of the decomposition is shown in Equation 2 and Equation 3.

$$\Delta V_i^{(T-0)} = V_i^T - V_i^0 = \Delta V_{ix_1}^{(T-0)} + \Delta V_{ix_2}^{(T-0)} + \cdots + \Delta V_{ix_k}^{(T-0)} \quad (2)$$

where  $\Delta V_i^{(T-0)}$  denotes the total volume of pollution discharge in the  $i$  province from the base year (0) to the target year (T). The right side of Equation 2 is the decomposition results according to  $k$  drivers. The decomposition of the  $j$  factor is shown in Equation 3.

$$\Delta V_{ix_j}^{(T-0)} = L(V_i^T, V_i^0) \ln \left( \frac{x_{j,i}^T}{x_{j,i}^0} \right) = \frac{V_i^T - V_i^0}{\ln V_i^T - \ln V_i^0} \ln \left( \frac{x_{j,i}^T}{x_{j,i}^0} \right) \quad (3)$$

The positive contribution degrees of the factors indicate that these factors can promote COD and  $\text{NH}_3\text{-N}$  discharge. The negative contribution degrees imply that the driving factors tend to inhibit COD and  $\text{NH}_3\text{-N}$  discharge.

### 2.2 The M-R decomposition

A spatial decomposition analysis was carried out to identify why differences exist among provinces, considering the COD and  $\text{NH}_3\text{-N}$  discharge and decomposition factors. The spatial analysis is conducted using data from a specific year and is called a single-year spatial analysis (Ang, 2015). When the spatial comparison group consists of  $I$  ( $i \geq 2$ ) regions, the literature recommends applying the M-R model (Ang et al., 2016; Wu and Zeng, 2013). The M-R model allows for calculated direct comparisons between each region and a previously calculated reference entity. In this research, the reference region is constructed. Its attributes are given by the arithmetic average of all the provinces included in China. The pollution discharge of the reference region is given by the weighted average of all the provinces. The same procedure is applied to calculate the remaining attributes of the reference region.

The spatial difference between one province  $i$  and the reference province in year  $T$  can be decomposed as follows:

TABLE 1 Description of variables in the LMDI and M-R models.

Symbols	Indication
$V_i^{In}$	The volume of industrial COD and NH <sub>3</sub> -N discharge in <i>i</i> province
$V_i^{ds}$	The volume of domestic COD and NH <sub>3</sub> -N discharge in <i>i</i> province
$W_i^{In}$	The volume of industrial wastewater discharge in <i>i</i> province
$W_i^{ds}$	The volume of domestic wastewater discharge in <i>i</i> province
$F_i^{In}$	The volume of industrial water consumption in <i>i</i> province
$F_i^{ds}$	The volume of domestic water consumption in <i>i</i> province
$A_i$	Industrial added value of <i>i</i> province
$G_i$	GDP of <i>i</i> province
$P_i^T$	The total population in <i>i</i> province
$P_i^U$	Urban population in <i>i</i> province
$ES_i$	The effect of economic scale in <i>i</i> province
$IS_i$	The effect of industrial structure in <i>i</i> province
$U_i$	The effect of urbanization in <i>i</i> province
$WI_i$	The effect of water intensity
$WDI_i$	The effect of wastewater discharge intensity
$PEI_i$	The effect of pollutant emission intensity

$$\Delta V^{(R_i-\bar{R})} = V^{R_i} - V^{\bar{R}} = \Delta V_{x_1}^{(R_i-\bar{R})} + \Delta V_{x_2}^{(R_i-\bar{R})} + \dots + \Delta V_{x_k}^{(R_i-\bar{R})}, \quad (4)$$

where  $\Delta V^{(R_i-\bar{R})}$  is the spatial difference of COD and NH<sub>3</sub>-N discharge between province *i* ( $V^{R_i}$ ) and the reference province in *t* year ( $V^{\bar{R}}$ ). The right side of Equation 4 is the decomposition results according to *k* drivers.  $\Delta V_{x_j}^{(R_i-\bar{R})}$  represents influencing effects that are defined as Equation 5:

$$\Delta V_{x_j}^{(R_i-\bar{R})} = L(V^{R_i}, V^{\bar{R}}) \ln \left( \frac{x_j^{R_i}}{x_j^{\bar{R}}} \right) = \frac{V^{R_i} - V^{\bar{R}}}{\ln V^{R_i} - \ln V^{\bar{R}}} \ln \left( \frac{x_j^{R_i}}{x_j^{\bar{R}}} \right) \quad (5)$$

## 2.3 The decomposition model proposed in this study

In this study, the driving factors of industrial COD and NH<sub>3</sub>-N discharge are decomposed into economic scale, industrial structure, and technology. Domestic COD and NH<sub>3</sub>-N drivers are decomposed into economic scale, urbanization, and technology. Concretely, the technical effect could be further decomposed into water intensity, wastewater discharge intensity, and pollutant emission intensity. Therefore, Equation 1 can be expressed as Equations 6, 7:

$$\begin{aligned} V^{In} &= \sum V_{ij}^{In} = \sum \frac{V_i^{In}}{W_i^{In}} \frac{W_i^{In}}{F_i^{In}} \frac{F_i^{In}}{A_i^{In}} \frac{A_i^{In}}{G_i} G_i \\ &= \sum PEI_i^{In} \cdot WDI_i^{In} \cdot WI_i^{In} \cdot IS_i^{In} \cdot ES_i^{In} \end{aligned} \quad (6)$$

$$\begin{aligned} V^{ds} &= \sum V_{ij}^{ds} = \sum \frac{V_i^{ds}}{W_i^{ds}} \frac{W_i^{ds}}{P_i^U} \frac{P_i^U}{P_i^T} \frac{P_i^T}{F_i^{ds}} \frac{F_i^{ds}}{G_i} G_i \\ &= \sum PEI_i^{ds} \cdot WDI_i^{ds} \cdot WI_i^{ds} \cdot U_i^{ds} \cdot ES_i^{ds} \end{aligned} \quad (7)$$

The definition and the statistical description of all the variables in the above equations are shown in Table 1.

## 2.4 The relative contribution rate of each factor

In order to take a comparison analysis of the contribution of the influencing effect within each region, the study adopted the relative contribution degree ( $\rho_{ij}$ ) indicated by the ratio of the contribution of each influencing effect to the absolute value of the change of pollutant discharge in the region, which is calculated according to Equation 8.

$$\rho_{ij} = \frac{\Delta V_{ij}}{\sum_j \Delta V_{ij}} \quad (8)$$

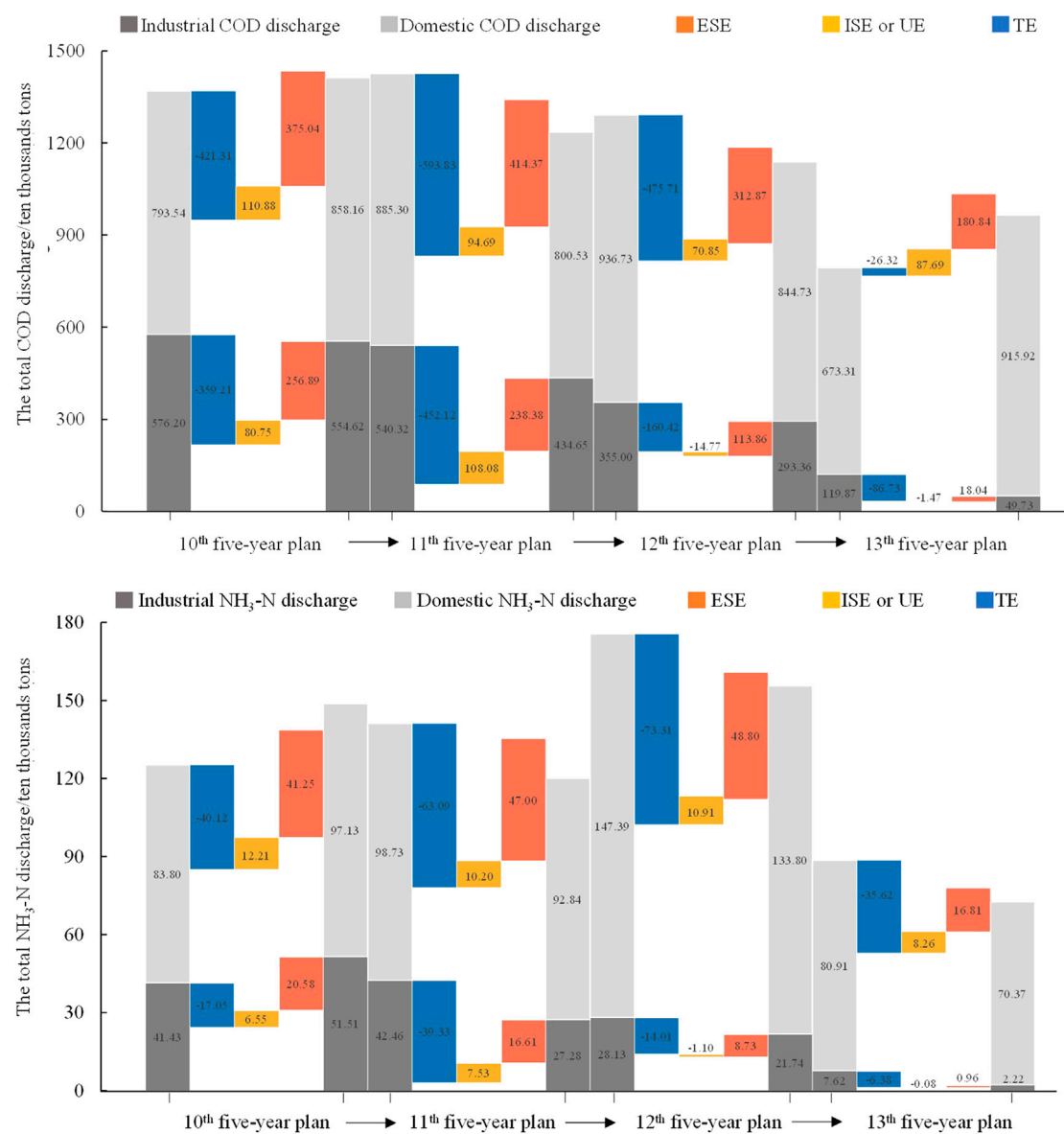
## 2.5 Data sources

Provincial wastewater, COD, and NH<sub>3</sub>-N discharge, respectively, from industrial and residential sources, covering the period from 2001 to 2020, were collected from the China Statistical Yearbook on Environment (2001–2020). GDP ( $G_i$ ), Industrial added value ( $A_i$ ), population ( $P_i^{tot}$ ) and urban population ( $P_i^U$ ) in each province are taken from the statistical yearbooks of each province in China (2001–2020).

## 3 Results and discussion

### 3.1 Influencing the contribution ratio of the drivers at the national level

According to the results shown in Figure 2, both industrial COD and NH<sub>3</sub>-N discharge showed a downward trend in China from 2001 to 2020 due to the combined effect of regional economic growth, industrialization or urbanization, and technological advances. However, the total volume of domestic pollution discharge is increasingly higher than that of industrial pollution discharge in China. This is because the effect of economic growth caused a sharp reduction in industrial pollution discharge but a slight decrease in domestic pollution discharge, although the ESE has played an important role in causing COD and NH<sub>3</sub>-N discharge. Meanwhile, urbanization led to more domestic COD and NH<sub>3</sub>-N discharge at high levels. Industrialization had a negative effect on industrial COD and NH<sub>3</sub>-N discharge reduction during the periods of the 10th and 11th Five-Year Plans. However, the effect has become positive in controlling industrial COD and NH<sub>3</sub>-N discharge since the 12th Five-Year Plan. Management and controls have been implemented systematically over industries with high wastewater pollutant discharge since 2001 in China, through the adjustment and optimization of industrial structure and enhanced environmental protection policy. Some industries have substantially reduced COD and NH<sub>3</sub>-N discharge, especially manufacturing and food processing, textile, paper and paper products, smelting and pressing of ferrous metals, and production and supply of electric powder and heat powder. Moreover, technological advances also contributed to the reduction of COD and NH<sub>3</sub>-N discharge. It can be seen from Figure 2 that the TE



**FIGURE 2** Decomposition of the influencing effects of COD and NH<sub>3</sub>-N discharge in China during the 10th, 11th, 12th, and 13th Five-Year Plans. ESE, ISE, UE, and TE, respectively, represent economic scale effect, industrialization effect, urbanization effect, and technology effect.

can significantly reduce the industrial wastewater discharge when it is high, but when the industrial wastewater discharge is reduced to a certain extent, the TE is limited. Consequently, the industrial COD and NH<sub>3</sub>-N discharges have been reduced to a small amount, but the domestic COD and NH<sub>3</sub>-N discharges still remained at a high level. Domestic COD discharge was increasing.

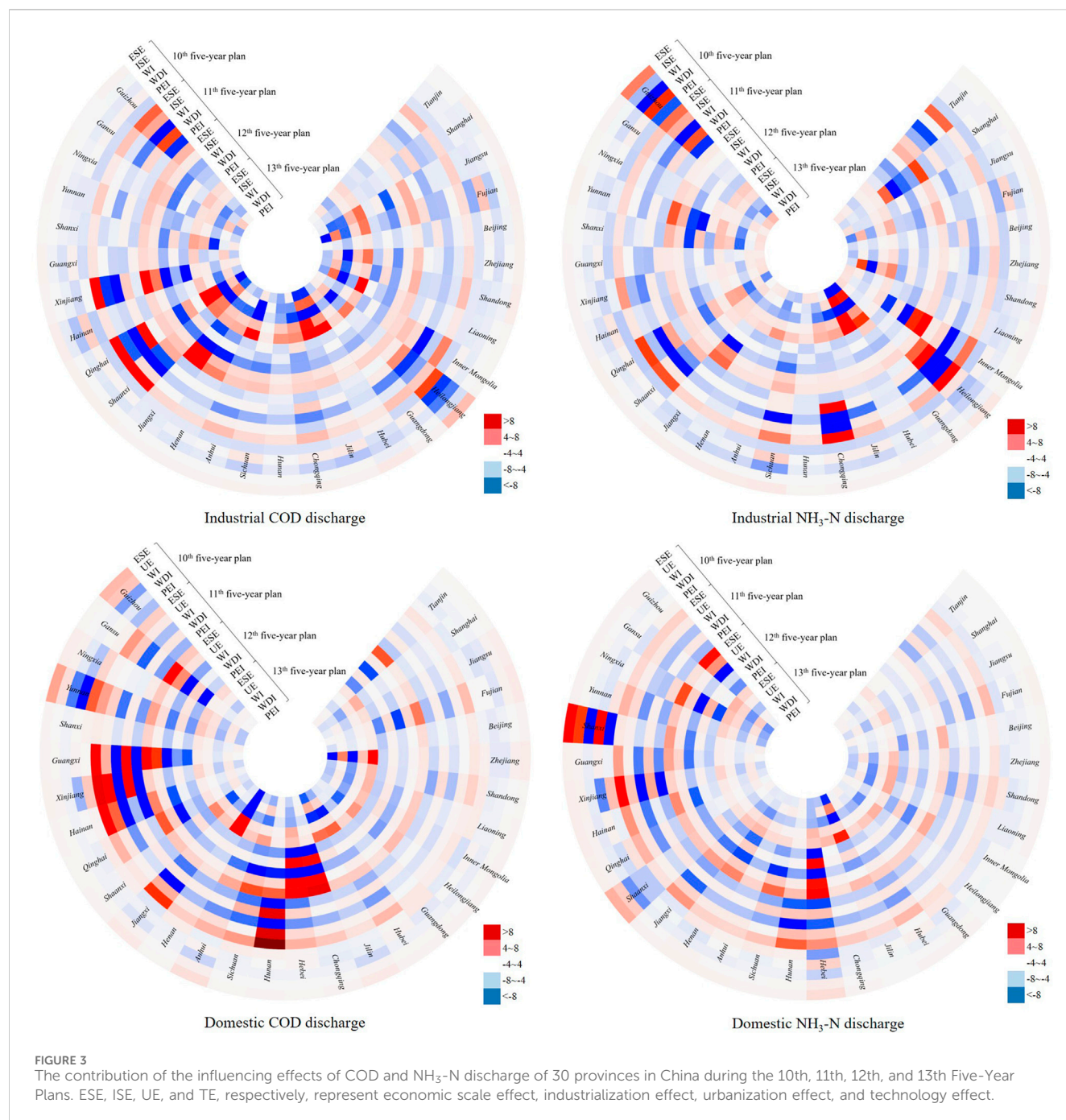
## 3.2 The temporal evolution of provincial decomposition analysis

### 3.2.1 The effect of economic scale

The results showed great differences by region in the temporal variation. Concretely, the ESE of all provinces was positively driven

from 2011 to 2020, whether industrial or domestic COD and NH<sub>3</sub>-N discharge. Changes of the ESE showed a varied history curve with different levels of economic development. As depicted in Figure 3, the ESE of industrial COD and NH<sub>3</sub>-N discharge in the eastern developed provinces has declined continuously since the 10th Five-Year Plan. The effect increased in part of middle China first and then decreased from the 12th Five-Year Plan, as did the northeast region, which is relatively backward in economic development. In the western region, where the economy lags, industrial COD and NH<sub>3</sub>-N discharge only began to decrease since the 13th Five-Year Plan. The results reveal that the levels of pollution first increase with economic growth and decline subsequently relative to economic growth at higher levels, which follows the environmental Kuznets curve (EKC) hypothesis (Chen et al., 2010).





The EKC relationship existed between economic growth and domestic COD and NH<sub>3</sub>-N discharge in China as well. However, quite a few areas, such as Anhui, Gansu, and Yunnan, have only reached the turning point of the EKC during the 13th Five-Year Plan. Thus, the ESE of some provinces declined, while others maintained a high level of domestic COD and NH<sub>3</sub>-N discharge.

### 3.2.2 The effect of industrial structure and urbanization

As shown in Figure 3, the ISE of most areas has turned positive due to the reduction of industrial COD and NH<sub>3</sub>-N discharge in the 13th Five-Year Plan. A few areas, such as Anhui, Hunan, Sichuan, Yunnan, and Jilin, still discharge more industrial pollution, which is

attributed to industrialization development. Industrial COD and NH<sub>3</sub>-N discharge in these provinces mainly came from the processing of food from agricultural products, the manufacture of foods, raw chemical materials, and chemical products. In addition, the manufacture of paper and paper products was a major contributor to industrial pollutant emissions in Anhui and Hunan. As a result of industrialization development, industrial wastewater pollution has been a serious problem in these areas. In the meantime, China was moving rapidly into urbanization. In all provinces, the UE has contributed to domestic COD and NH<sub>3</sub>-N discharge. During 2001–2020, the effects in some areas increased, while they decreased in other areas. The growth of the UE showed that the construction of urban environmental pollution treatment

facilities has not caught up with the need for environmental pollution discharge caused by population agglomeration in areas such as Guangdong, Fujian, Sichuan, Guizhou, and Xinjiang. Meanwhile, the domestic COD and  $\text{NH}_3\text{-N}$  discharge has decreased substantially in a few areas with high urbanization levels, including Shanghai, Tianjin, and Beijing. The results show that cities with high urbanization could increase efforts to improve infrastructure construction, facilitating the reduction of regional domestic COD and  $\text{NH}_3\text{-N}$  discharge.

### 3.2.3 The effect of technology

In the aspect of TE, the development level of technology varies in different areas, so its effect on COD and  $\text{NH}_3\text{-N}$  discharge reduction was uneven. The TE was all positive for the reduction of industrial COD and  $\text{NH}_3\text{-N}$  discharge. During the period of the 13th Five-Year Plan, the contribution of the TE of the industrial COD and  $\text{NH}_3\text{-N}$  discharge in each province in China tended to a similar degree. Concretely, the effects of industrial water intensity were always positive to water pollution reduction. The effects of pollutant intensity showed negative influences in the early stage and then changed gradually to positive influences in reducing industrial COD and  $\text{NH}_3\text{-N}$  discharge with time. In comparison, the contribution of industrial wastewater intensity in nearly half of China has shown a disincentive to pollution reduction at varying levels until the period of the 13th Five-Year Plan.

In the aspect of domestic COD and  $\text{NH}_3\text{-N}$  discharge, the TE also played a positive role in reducing pollution in the whole region from 2001 to 2015. However, half of the provinces had a small hindering effect on domestic pollution reduction during the period of the 13th Five-Year Plan. The WI (water intensity) effects were negative in all the provinces in China, which means technology advances of the WI reduce the domestic COD and  $\text{NH}_3\text{-N}$  discharge. In contrast, the WDI (wastewater discharge intensity) and PEI (pollutant emission intensity) effects increased discharge in many provinces. It suggests that the technical level of some areas has gradually failed to meet the growing demand for domestic COD and  $\text{NH}_3\text{-N}$  discharge and treatment as time advances. That is to say, the governance of the water environment in China should attach importance to technology advances for treating domestic COD and  $\text{NH}_3\text{-N}$  discharge.

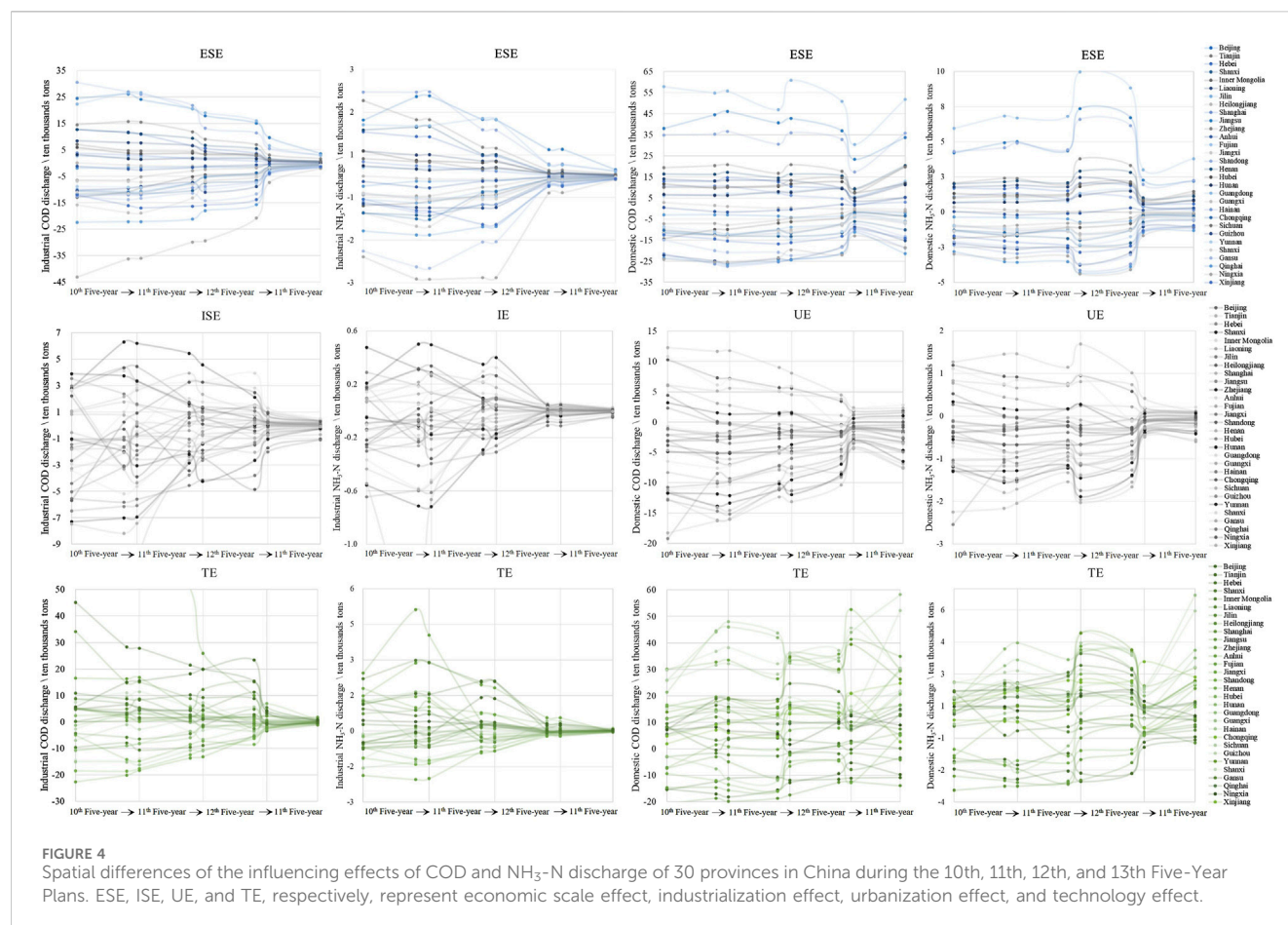
## 3.3 The spatial variation of provincial decomposition analysis

Overall, a great difference was noted in the spatial dynamic change of the drivers between industrial and domestic pollution discharge during 2001–2020, shown in Figure 4. The absolute value of each effect of industrial COD and  $\text{NH}_3\text{-N}$  discharge showed a decreasing trend, indicating that the gap between these provinces in China was narrowing during 2001–2020. However, not much has changed in the regional disparity related to the ESE and TE of domestic COD and  $\text{NH}_3\text{-N}$  discharge, and a slight reduction was shown in the UE of domestic pollution discharge.

In terms of industrial COD and  $\text{NH}_3\text{-N}$  discharge, the ESE values of 12 provinces are always positive, indicating that their economic growth caused more industrial COD and  $\text{NH}_3\text{-N}$  discharge than the average level of China, especially in Jiangsu,

Zhejiang, Guangdong, and Shandong, which had significantly higher values. In other words, the driving force of economic effects on industrial COD and  $\text{NH}_3\text{-N}$  discharge in China mainly came from the economic growth of eastern developed areas during 2001–2020. However, these regions have gradually shifted from extensive economic expansion to high-quality economic development. Their industrial structure adjustment currently has a good effect on reducing industrial pollutant discharge. As shown in Figure 4, the ISE contributions of Guangdong, Hebei, Henan, Jiangsu, Shandong, and Zhejiang were higher than those of the reference region in China. The ISE contributions also increased in some underdeveloped regions, such as Anhui, Jilin, Jiangxi, Inner Mongolia, Ningxia, and Shaanxi, through industrial structure upgrading and optimization. Thus, the average value of the ISE in China remained negative in the 13th Five-Year Plan, promoting the reduction of industrial pollutant discharge on the whole. Structural adjustment also plays a positive role in technological advancement (Wu and Zeng, 2013). Almost half of the provinces had a significantly higher TE contribution than the reference region. It is mainly because the contributions of cleaner production technology effects and industrial pollution treatment technology effects were high in these provinces. Some provinces had relatively low contributions to the TE but then increased significantly, changing from negative to positive. For example, wastewater reduction in important sectors has achieved remarkable results in Fujian through the construction of a green manufacturing system and technological innovation, shifting traditional industries toward circular economy industries. The provinces of Hebei, Hubei, and Shandong have significantly reduced pollutant discharge from industrial wastewater *via* the upgrading of traditional industries with high water consumption, such as steel manufacturing and chemical engineering.

In the aspect of domestic COD and  $\text{NH}_3\text{-N}$  discharge, the ESE of domestic COD and  $\text{NH}_3\text{-N}$  discharge in more than half of the provinces was also larger than the average value in China, in line with their contribution to industrial pollution discharge. The spatial structure of the ESE has not changed much in domestic COD and  $\text{NH}_3\text{-N}$  discharge, indicating that the improvement of regional economic levels has not alleviated the impact of economic expansion, driving the increase of domestic COD and  $\text{NH}_3\text{-N}$  discharge. Especially, the economic centers of China, such as Beijing, Shanghai, Guangdong, Zhejiang, and Tianjin, which drive the economic development of the surrounding areas, urbanization also has a relatively large driving impact on the emission of domestic pollutants. The UE in domestic COD and  $\text{NH}_3\text{-N}$  discharge was negative in most provinces but tended toward the average of China over time. In terms of the TE, the contributions of most provinces were positive. At the same time, a few provinces with better economic development were negative, including Beijing, Shanghai, Jiangsu, and Tianjin. That is to say, the TE in these provinces was lower than the average level of China, indicating that regional domestic sewage treatment capacity had not developed simultaneously in the process of economic growth and urbanization. Therefore, these regions should place greater emphasis on the improvement of domestic water conservation and the centralized treatment rate of domestic wastewater pollutants in the future.



## 4 Conclusions and future studies

### 4.1 Conclusions

Wastewater pollution discharge reduction is a comprehensive action that is intricately intertwined with socio-economic and environmental conditions, and the applicability and effectiveness of regional policy have become urgent concerns and exploration issues for water environment management under the new normal of China's economy. This study identified the current distribution, the contribution, and historical (temporal) changes of the influencing drivers, and the differences between industrial and domestic pollutants, serving as a more precise and differentiated decision and policy tool to effectively manage wastewater.

During the period of 2001–2020, the expansion of economic scale was the dominant positive driver of COD and NH<sub>3</sub>-N discharge of wastewater in China, and the effects of industrialization and urbanization were relatively limited. The technical effect was always the main solution to reducing emissions of COD and NH<sub>3</sub>-N. However, some provinces have entered the technological bottleneck stage of water pollutant treatment.

In terms of temporal evolution, most provinces have emission trends that are similar to those of the whole country. The ESE in the eastern developed provinces has declined first, then in parts of middle China and the northeast region, which are relatively

backward in economic development. The ESE in the western undeveloped region has only begun to decrease since the 13th Five-Year Plan, following the EKC hypothesis. ISE had increasing emission contributions during the 10th and 11th Five-Year Plans, but these became positive in industrial COD and NH<sub>3</sub>-N discharge reduction since the 12th Five-Year Plan. Meanwhile, the UE in all provinces contributed to domestic COD and NH<sub>3</sub>-N discharge. Over time, the effects of some areas increase and others decrease. During 2001–2020, the TE always had a positive influence on the reduction of industrial COD and NH<sub>3</sub>-N discharge in China. The TE in some provinces has shifted from a positive to a negative contribution to reducing domestic COD and NH<sub>3</sub>-N discharge since the 13th Five-Year Plan.

In terms of spatial variation, the contribution structure of each effect showed different characteristics between industrial and domestic pollution discharge as well. The gap among the spatial contributions related to the driving effects of industrial COD and NH<sub>3</sub>-N discharge narrowed with time, tending toward the national average. However, the contribution of each province held a relatively stable level, or showed a slight reduction, in terms of the influencing effects of domestic COD and NH<sub>3</sub>-N discharge. It showed the significant effectiveness of industrial structure adjustment, clean production, and the technology of industrial wastewater treatment across the country. As the industrial wastewater discharge was reduced to a certain extent, the influencing effects have been limited. With economic growth, the domestic sewage treatment



volume was still increasing, and the growth rate was faster than that of GDP in some provinces. The technology of many provinces had gradually failed to meet the growing demand for domestic sewage treatment. Consequently, the influencing contributions had significant regional differences among provinces. The governance of the water environment in China should attach importance to technology advances for domestic water conservation and wastewater treatment in the future.

## 4.2 Future studies

Overall, we believe that the modeling approach presented in this paper can be replicated in other regions of the world. As the largest developing country as well as the fastest-growing developing country, China's approach to wastewater pollution discharge and environmental issues is of great significance for other developing countries. This study not only helps to understand China's problem of wastewater pollutant emission but also provides a reference for other developing countries facing similar problems. In further research, the authors hope to improve the research methods for studying China's industrial and domestic wastewater pollution problems, using a smaller scale (for example, prefecture-level and county-level cities).

## Data availability statement

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

## Author contributions

CZ: conceptualization, funding acquisition, methodology, project administration, writing – original draft, and

writing – review and editing. YL: formal analysis and writing – review and editing. LL: formal analysis and writing – review and editing. YYo: data curation and writing – review and editing. YYe: data curation and writing – review and editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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## References

- Al-Mulali, U., Saboori, B., and Ozturk, I. (2015). Investigating the environmental Kuznets curve hypothesis in Vietnam. *Energy Policy* 76, 123–131. doi:10.1016/j.enpol.2014.11.019
- An, M., He, W., Degefu, D. M., Liao, Z., Zhang, Z., and Yuan, L. (2018). Spatial patterns of urban wastewater discharge and treatment plants efficiency in China. *Int. J. Environ. Res. Public Health* 15 (9), 1892. doi:10.3390/ijerph15091892
- Ang, B. W. (2015). LMDI decomposition approach: a guide for implementation. *Energy Policy* 86, 233–238. doi:10.1016/j.enpol.2015.07.007
- Ang, B. W., and Choi, K. H. (1997). Decomposition of aggregate energy and gas emission intensities for industry: a refined Divisia index method. *Energy J.* 18 (3), 59–73. doi:10.5547/issn0195-6574-ej-vol18-no3-3
- Ang, B. W., Su, B., and Wang, H. (2016). A spatial-temporal decomposition approach to performance assessment in energy and emissions. *Energy Econ.* 60, 112–121. doi:10.1016/j.eneco.2016.08.024
- Cai, H., Mei, Y., Chen, J., Wu, Z., Lan, L., and Zhu, D. (2020). An analysis of the relation between water pollution and economic growth in China by considering the contemporaneous correlation of water pollutants. *J. Clean. Prod.* 276, 122783. doi:10.1016/j.jclepro.2020.122783
- Chang, Y.-J., and Zhu, D. (2021). Water utilization and treatment efficiency of China's provinces and decoupling analysis based on policy implementation. *Resour. Conservation Recycl.* 168, 105270. doi:10.1016/j.resconrec.2020.105270
- Chen, D., Jin, G., Zhang, Q., Arowolo, A. O., and Li, Y. (2016). Water ecological function zoning in heihe river basin, northwest China. *Phys. Chem. Earth, Parts A/B/C* 96, 74–83. doi:10.1016/j.pce.2016.08.005
- Chen, K., Guo, Y., Liu, X., Jin, G., and Zhang, Z. (2019). Spatial-temporal pattern evolution of wastewater discharge in yangtze river economic zone from 2002 to 2015. *Phys. Chem. Earth, Parts A/B/C* 110, 125–132. doi:10.1016/j.pce.2019.01.005
- Chen, M., Lu, D., and Zha, L. (2010). The comprehensive evaluation of China's urbanization and effects on resources and environment. *J. Geogr. Sci.* 20 (1), 17–30. doi:10.1007/s11442-010-0017-0
- Cheng, J., Zou, R., Wang, H., and Geng, Z. (2022). How does China's industrial wastewater shadow price evolve? The perspective of spatiotemporal characteristics and differences decomposition. *Environ. Sci. Pollut. Res.* 29 (20), 30363–30382. doi:10.1007/s11356-021-17942-0
- ChinaNBoSo (2020). *ChinaNBoSo. China statistical yearbook on environment*. Beijing: China Statistics Press.
- Cole, M. A. (2004). Trade, the pollution haven hypothesis and the environmental Kuznets curve: examining the linkages. *Ecol. Econ.* 48 (1), 71–81. doi:10.1016/j.ecolecon.2003.09.007
- Dietz, T., and Rosa, E. A. (1997). Effects of population and affluence on CO2 emissions. *Proc. Natl. Acad. Sci. U. S. A.* 94 (1), 175–179. doi:10.1073/pnas.94.1.175
- Geng, Y. (2011). Improve China's sustainability targets. *Nature* 477 (7363), 162. doi:10.1038/477162b
- Geng, Y., Wang, M., Sarkis, J., Xue, B., Zhang, L., Fujita, T., et al. (2014). Spatial-temporal patterns and driving factors for industrial wastewater emission in China. *J. Clean. Prod.* 76, 116–124. doi:10.1016/j.jclepro.2014.04.047

- Grosman, G. M., and Krueger, A. B. (1994). Economic growth and the environment. *Q. J. Econ.* 110 (2), 353. doi:10.2307/2118443
- Grossman, G. M., and Krueger, A. B. (2025). Environmental impacts of a north-american free-trade agreement. *Garber PM, Editor* 1991. 13–56.
- Jeong, K., and Kim, S. (2013). LMDI decomposition analysis of greenhouse gas emissions in the Korean manufacturing sector. *Energy Policy* 62, 1245–1253. doi:10.1016/j.enpol.2013.06.077
- Jia, J., Jian, H., Xie, D., Gu, Z., and Chen, C. (2017). Multi-perspectives' comparisons and mitigating implications for the COD and NH<sub>3</sub>-N discharges into the wastewater from the industrial sector of China. *Water* 9 (3), 201. doi:10.3390/w9030201
- Jin, L., Zhang, G., and Tian, H. (2014). Current state of sewage treatment in China. *Water Res.* 66, 85–98. doi:10.1016/j.watres.2014.08.014
- Lee, C.-C., Chiu, Y.-B., and Sun, C.-H. (2010). The environmental Kuznets curve hypothesis for water pollution: do regions matter? *Energy Policy* 38 (1), 12–23. doi:10.1016/j.enpol.2009.05.004
- Li, J., See, K. F., and Chi, J. (2019). Water resources and water pollution emissions in China's industrial sector: a green-biased technological progress analysis. *J. Clean. Prod.* 229, 1412–1426. doi:10.1016/j.jclepro.2019.03.216
- Li, Q.-g., Liu, G.-h., Qi, L., Wang, H.-c., Ye, Z.-f., and Zhao, Q.-l. (2022). Heavy metal-contained wastewater in China: discharge, management and treatment. *Sci. Total Environ.* 808, 152091. doi:10.1016/j.scitotenv.2021.152091
- Li, R., Wang, Q., and Guo, J. (2024). Revisiting the environmental Kuznets curve (EKC) hypothesis of carbon emissions: exploring the impact of geopolitical risks, natural resource rents, corrupt governance, and energy intensity. *J. Environ. Manag.* 351, 119663. doi:10.1016/j.jenvman.2023.119663
- Liu, C., Cai, W., Zhai, M., Zhu, G., Zhang, C., and Jiang, Z. (2021). Decoupling of wastewater eco-environmental damage and China's economic development. *Sci. Total Environ.* 789, 147980. doi:10.1016/j.scitotenv.2021.147980
- Long, H., Lin, B., Ou, Y., and Chen, Q. (2019). Spatio-temporal analysis of driving factors of water resources consumption in China. *Sci. Total Environ.* 690, 1321–1330. doi:10.1016/j.scitotenv.2019.06.311
- Ma, B., Tian, G., and Kong, L. (2020). Spatial-temporal characteristics of China's industrial wastewater discharge at different scales. *Environ. Sci. Pollut. Res.* 27 (8), 8103–8118. doi:10.1007/s11356-019-07488-7
- Ozturk, I., Farooq, S., Majeed, M. T., and Skare, M. (2024). An empirical investigation of financial development and ecological footprint in South Asia: bridging the EKC and pollution haven hypotheses. *Geosci. Front.* 15 (4), 101588. doi:10.1016/j.gsf.2023.101588
- Panayotou, T. (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development. *Ilo Work. Pap.* 4.
- Rasul, G. (2016). Managing the food, water, and energy nexus for achieving the sustainable development goals in south asia. *Environ. Dev.* 18, 14–25. doi:10.1016/j.envdev.2015.12.001
- Robaina-Alves, M., Moutinho, V., and Costa, R. (2016). Change in energy-related CO<sub>2</sub> (carbon dioxide) emissions in Portuguese tourism: a decomposition analysis from 2000 to 2008. *J. Clean. Prod.* 111, 520–528. doi:10.1016/j.jclepro.2015.03.023
- Román-Collado, R., and Casado Ruiz, V. (2024). Key effects contributing to changes in energy imports in the EU-27 between 2000 and 2020: a decomposition analysis based on the Sankey diagram. *Energy Econ.* 140, 108009. doi:10.1016/j.eneco.2024.108009
- Ruan, F.-L., and Yan, L. (2022). Interactions among electricity consumption, disposable income, wastewater discharge, and economic growth: evidence from megacities in China from 1995 to 2018. *Energy* 260, 124910. doi:10.1016/j.energy.2022.124910
- Shahbaz, M., Sbiba, R., Hamdi, H., and Ozturk, I. (2014). Economic growth, electricity consumption, urbanization and environmental degradation relationship in United Arab Emirates. *Ecol. Indic.* 45, 622–631. doi:10.1016/j.ecolind.2014.05.022
- Shao, C., Guan, Y., Wan, Z., Guo, C., Chu, C., and Ju, M. (2014). Performance and decomposition analyses of carbon emissions from industrial energy consumption in Tianjin, China. *J. Clean. Prod.* 64, 590–601. doi:10.1016/j.jclepro.2013.08.017
- Shen, J. (2006). A simultaneous estimation of environmental Kuznets curve: evidence from China. *China Econ. Rev.* 17 (4), 383–394. doi:10.1016/j.chieco.2006.03.002
- Tian, C., Sui, H., Chen, Y., Wang, W., and Deng, H. (2025). Estimating carbon emission reductions from China's "Zero-waste City" construction pilot program. *Resour. Conservation Recycl.* 212, 107975. doi:10.1016/j.resconrec.2024.107975
- Tian, Y., Long, Z., and Li, Q. (2023). What are the determinants of wastewater discharge reduction in China? Decomposition analysis by LMDI. *Environ. Sci. Pollut. Res.* 30 (9), 23538–23552. doi:10.1007/s11356-022-23887-9
- Vincent, J. R. (1997). Testing for environmental Kuznets curves within a developing country. *Environ. Dev. Econ.* 2 (4), 417–431. doi:10.1017/s1355770x97000223
- Wang, M., and Feng, C. (2017). Decomposition of energy-related CO<sub>2</sub> emissions in China: an empirical analysis based on provincial panel data of three sectors. *Appl. Energy* 190, 772–787. doi:10.1016/j.apenergy.2017.01.007
- Wei, X., Wang, J., Wu, S., Xin, X., Wang, Z., and Liu, W. (2019). Comprehensive evaluation model for water environment carrying capacity based on VPOSRM framework: a case study in Wuhan, China. *Sustain. Cities Soc.* 50, 101640. doi:10.1016/j.scs.2019.101640
- Wu, L., and Zeng, W. (2013). Research on the contribution of structure adjustment on carbon dioxide emissions reduction based on LMDI method. *Procedia Comput. Sci.* 17, 744–751. doi:10.1016/j.procs.2013.05.096
- Xie, Y., Zeng, L., Wang, P., Wu, X., and Feng, T. (2022). Water cost for water purification: renewability assessment of a typical wastewater treatment plant in China. *J. Clean. Prod.* 349, 131474. doi:10.1016/j.jclepro.2022.131474
- Xu, C., Chen, W., and Hong, J. (2014). Life-cycle environmental and economic assessment of sewage sludge treatment in China. *J. Clean. Prod.* 67, 79–87. doi:10.1016/j.jclepro.2013.12.002
- Yang, G., Zhang, G., and Wang, H. (2015). Current state of sludge production, management, treatment and disposal in China. *Water Res.* 78, 60–73. doi:10.1016/j.watres.2015.04.002
- Yao, L., He, L., and Chen, X. (2019). Scale and process design for sewage treatment plants in airports using multi-objective optimization model with uncertain influent concentration. *Environ. Sci. Pollut. Res.* 26 (14), 14534–14546. doi:10.1007/s11356-019-04622-3
- Zhang, C., Wang, Y., Song, X., Kubota, J., He, Y., Tojo, J., et al. (2017). An integrated specification for the nexus of water pollution and economic growth in China: panel cointegration, long-run causality and environmental Kuznets curve. *Sci. Total Environ.* 609, 319–328. doi:10.1016/j.scitotenv.2017.07.107
- Zhang, Z., Li, Y., Wang, X., Xu, Y., Liao, Y., Wan, Z., et al. (2021). Investigating the spatiotemporal dynamic evolution and driving factors of wastewater treatment efficiency in the context of China's River Chief system. *Ecol. Indic.* 129, 107991. doi:10.1016/j.ecolind.2021.107991
- Zhao, C., and Chen, B. (2014). Driving force analysis of the agricultural water footprint in China based on the LMDI method. *Environ. Sci. and Technol.* 48 (21), 12723–12731. doi:10.1021/es503513z