Multi-perspective comparisons and mitigation implications of SO₂ and NO_x discharges from the industrial sector of China: a decomposition analysis

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Abstract

This study is the first attempt to investigate the drivers of Chinese industrial SO₂ and NO_x emissions from both periodic and structural perspectives through a decomposition analysis using the logarithmic mean Divisia index (LMDI). The two pollutants' emissions were decomposed into output effects, structural effects, clean production effects, and pollution abatement effects. The results showed that China's industrial SO₂ discharge increased by 1.14 Mt during 2003–2014, and the contributions from the four effects were 23.17, –1.88, –3.80, and –16.36 Mt, respectively. Likewise, NO_x discharge changed by –3.44 Mt over 2011–2014, and the corresponding contributions from the four effects were 2.97, –0.62, –1.84, and –3.95 Mt. Thus, the output effect was mainly responsible for the growth of the two discharges. The average annual contribution rates of SO₂ and NO_x from output were 14.33 and 5.97%, respectively, but pollution abatement technology presented the most obvious mitigating effects (–10.11 and –7.92%), followed by the mitigating effects of clean production technology (–2.35 and –3.7%), and the mitigation from the structural effect was the weakest (–1.16 and –1.25%, respectively), which meant pollutant reduction policies related to industrial structure adjustment should be a long-term measure for the two discharges. In addition, the sub-sectors of I20 (manufacture of raw chemical materials and chemical products), I24 (manufacture of non-metallic mineral products), and I26 (smelting and pressing of non-ferrous metals) were the major contributors to both discharges. Thus, these sub-sectors should be given priority consideration when designing mitigation-related measures. Last, some particular policy implications were recommended for reducing the two discharges, including that the government should seek a technological discharge reduction route.

Keywords Multi-perspective · Decomposition analysis · Industrial SO₂ and NO_x discharges · LMDI · China

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Introduction

Reducing sulfur dioxide (SO₂) and nitric oxide (NO_x) pollution is one of the most concerning global issues (Radoiu et al. 2003; McDonald-Buller et al. 2016). Decreasing the discharge of these two air pollutants has an important significance for a cleaner atmosphere and environment and improved public (Xie et al. 2004; Blanchard et al. 2005; Muller et al. 2009; de Gouw et al. 2014). In fact, scientists have analyzed their trends and source characteristics, expecting to discover some physical methods or policy tools to remove the pollutants (Popp 2006; Fraley et al. 2006; Washenfelder et al. 2010; Fang et al. 2011; Hansjurgens 2011; Lu et al. 2013; Pinkerton 2014; Lee and Zhou 2015; Jacimovski et al. 2016). For example, Mekaroonreung and Johnson (2012) used the stochastic semi-non-parametric envelopment method to estimate the shadow prices of SO₂ and NO_x generated by US coal power plants. They proposed a price mechanism to inhibit the two pollutants' emissions. Sun et al. (2016) provided a detailed description of SO₂ and NO_x resources and summarized the currently used techniques to remove them in order to protect the atmospheric environment. In addition, by introducing new energy such as solar, wind, and fuel cells, controlling air pollutants had been discussed and programmed by some optimization models to satisfy the atmosphere quality demands in a cost-effective manner (Chen et al. 2016, 2017; Li et al. 2017; He et al. 2017). Thus, it is currently necessary to study this problem in depth from some other perspectives.

China's gross domestic product (GDP) has experienced rapid growth since 1978 that has made it the fastest growing country (Zhang and Wen 2008). Similarly, its industrial GDP also showed a remarkable growth. In 2003, the Chinese industrial GDP was valued at 7.47 trillion Chinese yuan (CNY), but it increased to 22.34 trillion CNY in 2014 with an annual average increase of 10.47%. The smallest increase was 6.93% in 2014 (Fig. 1a). This rapid economic development coupled with industrialization, urbanization, and inadequate investments in basic air treatment infrastructure resulted in widespread atmospheric pollution in China (Lei et al. 2012). Therefore, more attention has been paid to whether the country's development is sustainable and when and how its environmental conditions will be improved. For example, it was projected that China's government should reduce SO₂ and NO_x emissions by an annual decreasing rate of 8 and 10%, respectively, while retaining an average annual GDP growth rate of no less than 7% during its 12th Five-Year Plan (2011–2015). As a result, the real mitigating effects (18 and 18.6% for SO₂ and NO_x, respectively) and the GDP growth (7.8%) were reported in the first chapter of China's 13th Five-Year Plan (2016–2020; Xinhua News Agency 2016). The discharges of the two pollutants decreased from 2011 to 2014, and the corresponding discharge intensities (discharge per GDP) also obviously decreased from 2011 to

2014 (Fig. 1b). Traditionally, with the development of economy, it was considered that the pollutants' discharge would show an *inverted-U* shape trend (Grossman and Krueger 1991). However, this was not the sole possible relationship between economic development and pollutant discharges (Douglas and Thomas 1995; Friedl and Getzner 2003), as seen in the abrupt increase of SO₂ from 2010 to 2011 (Fig. 1b). Thus, some other methods and/or new perspectives are needed to study this problem in China.

Some scholars explored China's SO₂ and NO_x discharges from the perspectives of agriculture (Yang et al. 2002), transportation, aviation (Qu et al., 2016; Fan et al., 2012), trends, characteristics (Wang et al. 2002; Tian et al. 2013; Song and Yang 2014), scenarios, forecasting (Vallack et al. 2001; Lu et al. 2014), and the radiative transfer (Sun et al. 2006). Some other scholars have studied the relationship between the two pollutants and respiratory diseases (Ma et al. 2016), their co-benefits with carbon reduction (Nam et al. 2013), and the assessment of related mitigation policies or strategies (Graus and Worrell 2007; Ying et al. 2007; Zhao et al. 2013; Peng et al. 2016). However, few scientists have studied the drivers of SO₂ and NO_x discharges in China from both the periodic Five-Year Plan and the industrial structural perspectives. Therefore, it is necessary for us to accomplish this objective in this paper.

There are two commonly used methods in the similar studies (Liu et al. 2016; Xiao et al. 2016): structural decomposition analysis (SDA) and index decomposition analysis (IDA). SDA often requires the economic data of an input–output table, while IDA only needs the aggregate data of each industrial category (Cellura et al. 2012; Cansino et al. 2016; Yang et al. 2016). In addition, SDA can only analyze the change between the limited years, while IDA usually can analyze the change across any years (Hoekstra and van der Bergh 2003). Therefore, based on the available data, the IDA model was adopted for this study, despite the fact that there are still many optional indices for quantifying the impacts of factorial changes on the aggregated industrial sector. These indices include the Laspeyres index (Lu et al., 2014a, b), the Paasche index (Liu et al. 2016), the arithmetic mean Divisia index (Hatzigeorgiou et al. 2008), and the logarithmic mean Divisia index (LMDI; Ang 2005; Wang et al. 2005; Lee and Oh 2006; Wood and Lenzen 2006). Among them, the LMDI has become the most popular due to its incomparable advantages (Chen 2011; Tan et al. 2011; Ren et al. 2012; Zhang et al. 2013; Tian et al., 2013a, b; Shao et al. 2016). Therefore, the LMDI decomposition was chosen for this study. The remainder of this paper is organized as follows: the LMDI decomposition model and the corresponding data explanation are presented in the “Data and methodology” section, the results and related discussions are presented in the “Results and discussion” section, and some conclusions and particular strategies or policy implications for mitigating Chinese SO₂ and

Fig. 1 **a** Chinese industrial GDP and its growth rate from 2003 to 2014. **b** Chinese SO₂ (2003–2014) and NO_x (2011–2014) discharges and their respective intensities

NO_x discharges (especially in the industrial sector) are contained in the “Conclusions and policy implications” section.

Data and methodology

Data explanation

China publishes its official statistics of atmospheric pollutants annually in the China Statistical Yearbook on Environment (CSYE). However, the pollutant data for NO_x is not available until 2011. Thus, the time series data of SO₂ from 2003 to 2014 and that of NO_x from 2011 to 2014 are extracted (<http://www.stats.gov.cn/ztc/ztsj/hjtjzl/>). Based on the studied period, the related economic data can be acquired from the corresponding China Statistical Yearbook (CSY). The amount and share of ancillary activities for exploitation (AAEs) are marginal, and those of AAEs of SO₂ or NO_x discharges are close to 0 in most years. Therefore, the AAE industry is excluded. Similarly, some other industries are also excluded (<http://www.stats.gov.cn/tjsj/nds/>). Overall, 38 industrial sub-sectors were investigated (Table 1).

It is worth noting that the national statistics are revised when an economic census is completed, and the revisions will be published in the next year. Moreover, in order to eliminate the influence of price changes on the raw economic data, they are deflated from the current prices to constant 2010 prices using the corresponding price indices. Since the price indices are not available at the industrial sub-sector level, the price indices of the entire industrial sector are used to replace them.

LMDI decomposition model

To illustrate how the LMDI works, some related variables are listed in Table 2. The aggregate industrial SO₂ or NO_x discharges are expressed as Y in Eq. 1. It is decomposed as the economic output effect (G), the industrial structure effect (S), and the intensity effect (I). I can somewhat reflect the technological level's progress (Sun 1998) and can be further divided into the effects of

cleaner production (C) and pollution abatement (A). C is the production of the two pollutants per unit of GDP, and A is the ratio of the pollutant's discharge divided by the production's amount. Therefore, C and A can somewhat reflect the developmental status of cleaner production technologies (CPTs) and pollution abatement technologies (PATs), respectively. The CPT focuses on the management of these pollutants' sources and the reuse of resources during the process of production, whereas PAT only focuses on the pollution end-controlling.

$$Y = \sum_{i=1}^{38} \frac{Y_i}{G} \times G = \sum_{i=1}^{38} \frac{Y_i}{G_i} \times \frac{G_i}{G} \times G = \sum_{i=1}^{38} \frac{Y_i}{E_i} \times \frac{E_i}{G_i} \times \frac{G_i}{G} \times G \quad (1)$$

Therefore, by taking the logarithmic differentiation of Eq. (1) based on the time, the following identity is obtained:

$$\frac{d \ln Y}{dt} = \sum_{i=1}^{38} \left[\phi_i \times \left(\frac{d \ln A_i}{dt} + \frac{d \ln C_i}{dt} + \frac{d \ln S_i}{dt} + \frac{d \ln G}{dt} \right) \right] \quad (2)$$

where $\phi_i(t) = \frac{A_i \cdot C_i \cdot S_i \cdot G}{Y} = \frac{A_i \cdot C_i \cdot S_i \cdot G}{Y}$.

By integrating Eq. (2) over the time interval $[0, T]$, Eq. (3) is obtained

$$\ln \frac{Y_T}{Y_0} = \sum_{i=1}^{38} \int_0^T \phi_i(t) \times \left(\frac{d \ln A_i}{dt} + \frac{d \ln C_i}{dt} + \frac{d \ln S_i}{dt} + \frac{d \ln G}{dt} \right) \times dt \quad (3)$$

Then, the exponentiation of Eq. (3) is obtained

$$\frac{Y_T}{Y_0} = \exp \left(\sum_{i=1}^{38} \int_0^T \phi_i(t) \frac{d \ln A_i}{dt} dt \right) \times \exp \left(\sum_{i=1}^{38} \int_0^T \phi_i(t) \frac{d \ln C_i}{dt} dt \right) \times \exp \left(\sum_{i=1}^{38} \int_0^T \phi_i(t) \frac{d \ln S_i}{dt} dt \right) \times \exp \left(\sum_{i=1}^{38} \int_0^T \phi_i(t) \frac{d \ln G}{dt} dt \right) \quad (4)$$

In accordance with the definite integral middle value theorem, Eq. (4) is transformed as

$$\frac{Y_T}{Y_0} = \exp \left(\sum_{i=1}^{38} \varphi_i(t^*) \ln \frac{A_{i,T}}{A_{i,0}} \right) \times \exp \left(\sum_{i=1}^{38} \varphi_i(t^*) \ln \frac{C_{i,T}}{C_{i,0}} \right) \times \exp \left(\sum_{i=1}^{38} \varphi_i(t^*) \ln \frac{S_{i,T}}{S_{i,0}} \right) \times \exp \left(\sum_{i=1}^{38} \varphi_i(t^*) \ln \frac{G_T}{G_0} \right) \quad (5)$$

Table 1 Classification of industrial sub-sectors studied in this paper

No.	Sector
I1	Mining and washing of coal
I2	Extraction of petroleum and natural gas
I3	Mining and processing of ferrous metal ores
I4	Mining and processing of non-ferrous metal ores
I5	Mining and processing of non-metal ores
I6	Mining of other ores
I7	Processing of food from agricultural products
I8	Manufacture of foods
I9	Manufacture of beverages
I10	Manufacture of tobacco
I11	Manufacture of textile
I12	Manufacture of textile wearing apparel, footwear, and caps
I13	Manufacture of leather, fur, feather, and related products
I14	Processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products
I15	Manufacture of furniture
I16	Manufacture of paper and paper products
I17	Printing, reproduction of recording media
I18	Manufacture of articles for culture, education, and sport
I19	Processing of petroleum, coking, processing of nuclear fuel
I20	Manufacture of raw chemical materials and chemical products
I21	Manufacture of medicines
I22	Manufacture of chemical fibers
I23	Manufacture of rubber and plastics
I24	Manufacture of non-metallic mineral products
I25	Smelting and pressing of ferrous metals
I26	Smelting and pressing of non-ferrous metals
I27	Manufacture of metal products
I28	Manufacture of general purpose machinery
I29	Manufacture of special purpose machinery
I30	Manufacture of transport equipment
I31	Manufacture of electrical machinery and equipment
I32	Manufacture of communication equipment, computers, and other electronic equipment
I33	Manufacture of measuring instruments and machinery for cultural activity and office work
I34	Manufacture of artwork and other manufacturing
I35	Recycling and disposal of waste
I36	Production and supply of electric power and heat power
I37	Production and supply of gas
I38	Production and supply of water

where $\phi_i(t^*)$ is the weight function given by $\phi_i(t) = \frac{Y_i}{Y}$ at point $t^* \in [0, T]$.

According to the log mean weight function recommended by Ang and Liu (2001), the weight function of $\phi_i(t^*)$ is expressed as

$$\phi_i(t^*) = \frac{L(Y_{i,T}, Y_{i,0})}{L(Y_T, Y_0)} \quad (6)$$

where the logarithmic mean of two positive numbers is

$$L(x, y) = \begin{cases} (x-y)/(\ln x - \ln y), & x \neq y > 0 \\ x, & x = y > 0 \end{cases} \quad (7)$$

Thus, Eq. (5) can be simplified as

$$\Psi Y_{\text{tot}} = Y_T/Y_0 = \Psi Y_I \times \Psi Y_S \times \Psi Y_G = \Psi Y_A \times \Psi Y_C \times \Psi Y_S \times \Psi Y_G \quad (8)$$

where

$$\Psi Y_I = \exp \left(\sum_{i=1}^{38} \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \times \ln \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \right),$$

$$\Psi Y_S = \exp \left(\sum_{i=1}^{38} \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \times \ln \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \right),$$

$$\Psi Y_G = \exp \left(\sum_{i=1}^{38} \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \times \ln \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \right),$$

$$\Psi Y_C = \exp \left(\sum_{i=1}^{38} \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \times \ln \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \right),$$

Equation (8) is the multiplicative formation of the LMDI decomposition (Shao et al. 2016), where ΨY_{tot} is the total multiplicative changes of the discharges from year 0 (Y_0) to T (Y_T). ΨY_I , ΨY_S , ΨY_G , ΨY_A , and ΨY_C are the respective multiplicative forms of the intensity effect, the structure effect, the output effect, the pollution abatement effect, and the clean production effect. The corresponding additive formation of the LMDI decomposition is written as Eq. (9)

$$\begin{aligned} \Psi Y_{\text{tot}} &= Y_T - Y_0 = \Delta Y_I \times \Delta Y_S \times \Delta Y_G \\ &= \Delta Y_A \times \Delta Y_C \times \Delta Y_S \times \Delta Y_G \end{aligned} \quad (9)$$

$$\text{where } \Delta Y_I = \sum_{j=1}^{38} \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}} \cdot \ln \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}},$$

$$\Delta Y_S = \sum_{j=1}^{38} \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}} \cdot \ln \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}},$$

$$\Delta Y_G = \sum_{j=1}^{38} \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}} \cdot \ln \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}},$$

$$\Delta Y_A = \sum_{j=1}^{38} \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}} \cdot \ln \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}},$$

$$\Delta Y_C = \sum_{j=1}^{38} \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}} \cdot \ln \frac{Y_{j,T}-Y_{j,0}}{\ln Y_{j,T}-\ln Y_{j,0}}.$$

ΔY_{tot} is the total additive changes of the discharges from year 0 (Y_0) to T (Y_T). ΔY_I , ΔY_S , ΔY_G , ΔY_A , and ΔY_C are the respective corresponding additive forms of the intensity effect, the structure effect, the output effect, the pollution abatement effect, and the clean production effect.

Table 2 Summary of variables and their meanings

Variables	Meaning of variables	Unit
$Y_{i,T}, Y_{i,0}$	Industrial pollutant discharge in sector i in years T and 0, respectively	t
Y_T, Y_0	Total industrial pollutant discharge in year T and year 0, respectively	t
$E_{i,T}, E_{i,0}$	Industrial pollutant production in sector i in years T and 0, respectively	t
E_T, E_0	Total industrial pollutant production in year T and year 0, respectively	t
$G_{i,T}, G_{i,0}$	Output of industrial sector i in year T and year 0, respectively	CNY
G_T, G_0	Gross industrial output in year T and year 0, respectively	CNY
$S_{i,T}, S_{i,0}$	Output share of industrial sub-sector i in year T and year 0, respectively	%
$I_{i,T}, I_{i,0}$	Discharge intensity in sector i in year T and year 0, respectively	t/CNY
$C_{i,T}, C_{i,0}$	Production intensity in sector i in year T and year 0, respectively	t/CNY
$A_{i,T}, A_{i,0}$	Discharge rate in sector i in year T and year 0, respectively	%
$\Psi Y_{\text{tot}}, \Delta Y_{\text{tot}}$	Change in industrial pollutant discharge from years 0 to T	–, t
$\Psi Y_G, \Delta Y_G$	Output effect on the aggregate industrial discharge	–, t
$\Psi Y_S, \Delta Y_S$	Structural effect on the aggregate industrial discharge	–, t
$\Psi Y_I, \Delta Y_I$	Intensity effect on the aggregate industrial discharge	–, t
$\Psi Y_C, \Delta Y_C$	Clean technologies' effect on the aggregate industrial discharge	–, t
$\Psi Y_A, \Delta Y_A$	Pollution abatement effect on the aggregate industrial discharge	–, t

The minus sign denotes the corresponding indicator had only the absolute number and no unit

Results and discussion

Comparisons of various stages from periodic perspective

Every period of the Five-Year Plan can be regarded as one stage, and the decomposition results at each stage can be compared. The end of the 10th Five-Year Plan (2003–2005) was sorted as the first stage. Therefore, SO₂ changes were in three continuous stages, and NO_x was only in one stage. The multiplicative decomposition results of these various stages are presented in Figure S1. The corresponding additive decomposition results are listed in Fig. 2. Their detailed results are shown in Tables S2 and S3, respectively.

Obviously, China's SO₂ increased by 4.84 million tons (Mt) from 2003 to 2005 (Fig. 2a; Table S2), with a growth rate of 33% (Table S1) at the first stage. Then, it decreased by 2.61 Mt with the change rate of –13% (Fig. 2b; Tables S2 and S3). In the third stage (2010–2014), it still decreased by 1.09 Mt with the change rate of –6% (Fig. 2c; Tables S2 and S3). However, China's SO₂ emissions still experienced an overall increase (Fig. 1b) of 1.14 Mt or 8% (Tables S2 and S3). Similarly, China's NO_x decreased by 3.44 Mt from 2011 to 2014 (Figs. 1b and 3; Table S2), with a change rate of –21% (Table S1).

Table 3 shows the contributions of various factors to the two pollutants' changes, which were calculated through the additive results in Table S2. Here, the contributions refer to the proportions of pollutant changes caused by each factor at time T (i.e., the additive decomposition result of each factor) in the

total EICE at time 0. Contributions were ordered from high to low during 2003–2014 as follows: the mitigating factors of the SO₂ discharge in China were the pollution abatement effect (–111.24%), the clean production effect (–25.87%), and the industrial structure (–12.78%), while the promotion factor was only output (157.62%). The promotion effect (157.62%) was still much greater than the total mitigating effects (–111.24% – 25.87% – 12.78% = –149.89%), which caused a slight increase of 7.72% in the total SO₂ discharge from 2003 to 2014 (Table 3). Similarly, the mitigating factors of the NO_x discharge were the pollution abatement effect (–23.77%), the clean production effect (–11.10%), and the industrial structure (–3.75%), while the promotion factor was also only output (17.90%). Conversely, the promotion effect (17.90%) was less than the total mitigating effects (–23.77% – 11.10% – 3.75% = –38.62%). Thus, this fact caused an obvious decrease of 20.72% in the total NO_x discharge during 2011–2014 (Table 3).

Output effect

To smooth the short-term volatile effects of various factors (Ma and Stern 2008; Shao et al. 2016), the cumulative decomposition result converted from the multiplicative decomposition results of Table S1 is listed in Table S3 and depicted in Fig. 3. The contribution results and change' trends of each effect at different stages are shown in Fig. 4 and Table 4, respectively. It can be easily found that only output remained as a positive effect on the two pollutant discharges and presented a sharp upward trend during 2003–2014 (ΨY_G in Fig. 3). This

Fig. 2 The additive decomposition results of China's SO₂ changes in the three Five-Year Plan periods and NO_x in the 12th Five-Year Plan period. ΔY_{tot} , ΔY_A , ΔY_C , ΔY_S , and ΔY_G denoted the respective total changes of the two pollutants' discharges and the effects of pollution abatement, clean production, industrial structure, and output. **a** SO₂ in 2003–2005. **b** SO₂ in 2005–2010. **c** SO₂ in 2010–2014. **d** NO_x in 2011–2014

result indicated the dominant effect of output expansion on discharge growth.

Particularly, the multiplicative and additive decomposition effects of the output on the SO₂ discharge were 1.56 and 7.58 Mt at the first stage (2003–2005, Figure S1a and 3a), respectively. At the second stage (2005–2010), the decomposition effects on the SO₂ discharge were 2.20 and 14.31 Mt (Figure S1b and 3b). The promotion effect of output on SO₂ growth had an obvious increase. At the third stage (2010–2014), the decomposition effects were 1.37 and 5.10 Mt (Figure S1c and 3c). The promotion effect of output had a slight decrease. Overall, the output effect on SO₂ discharge had the largest average annual contribution rate (14.33%) over the others (Table 4). In the various three stages, the corresponding average annual contribution rates were 25.77, 14.65, and 7.53% (Table 4). These conclusions were consistent with this and Fig. 4.

Similarly, the multiplicative and additive decomposition effects of the output on NO_x discharge were 1.22 and 2.97 Mt during period 2011–2014 (Figure S1d and 3d), respectively. The output effect on NO_x discharge had also the largest average annual contribution rate (5.97%) over the others (Table 4) and had always the positive effects (Table 3). These results meant that the industrial output growth was also the most prominent driving factor for NO_x growth and consistent with the previous results.

Structure effect

After the 2008 global financial crisis, the sustainable development of the social economy received increasing attention. Moreover, the transformation of the industrial structure received great impetus as a result of some

Fig. 3 Indices' trends of cumulative decomposition results of SO₂ and NO_x changes. ΨY_{tot} , ΨY_A , ΨY_C , ΨY_S , and ΨY_G denoted the total change and the effects' indices of pollution abatement, clean production, industrial structure, and output on the two discharges, respectively

Table 3 Contributions of various factors to the SO₂ (first 18 lines) and NO_x (last 5 lines) changes (unit: %)

Stage	Changes	Intensity	Pollution abatement	Clean production	Structure	Output
2003–2004	17.30	–18.54	–0.53	–18.01	–2.67	38.51
2004–2005	13.28	0.66	2.10	–1.44	2.97	9.64
2005–2006	2.28	–14.75	–14.70	–0.05	–2.66	19.69
2006–2007	–1.70	–14.99	–20.61	5.62	–3.47	16.75
2007–2008	–6.58	–17.36	–5.69	–11.67	–3.63	14.41
2008–2009	–7.76	–16.93	–18.59	1.66	0.75	8.42
2009–2010	–0.02	–16.4	–20.24	3.84	–3.43	19.81
2010–2011	11.99	0.76	–9.63	10.39	–0.65	11.88
2011–2012	–6.35	–14.31	–0.92	–13.39	0.59	7.37
2012–2013	–4.89	–10.49	–10.43	–0.06	–2.73	8.33
2013–2014	–6.19	–7.7	–9.54	1.84	–2.38	3.90
2003–2005	32.89	–18.74	1.57	–20.31	0.08	51.54
2005–2010	–13.38	–75.77	–74.73	–1.04	–10.83	73.22
2010–2014	–6.42	–31.6	–30.03	–1.57	–4.95	30.13
2003–2014	7.72	–137.11	–111.24	–25.87	–12.78	157.62
2011–2012	–4.78	–13.38	–1.87	–11.51	1.16	7.43
2012–2013	–7.33	–12.25	–13.79	1.54	–3.30	8.22
2013–2014	–10.16	–12.05	–10.75	–1.30	–1.91	3.81
2011–2014	–20.72	–34.87	–23.77	–11.10	–3.75	17.90

The minus sign denotes the positive (favorable) contribution of mitigating the SO₂ or NO_x discharge

effective pollution reduction actions of the government. As a result, the proportion of tertiary industry output increased from 42.9% in 2008 to 48.1% in 2014. Therefore, it could be found that these pollutant reduction efforts (such as updating the industrial structure) surely had a positive effect on mitigating the two pollutants' discharges. For example, the industrial structure adjustment presented an overall mitigating effect on SO₂ discharge from 2003 to 2014 when the average annual contribution rate was –1.16% (Table 4). In the various three stages, the corresponding average annual contribution rates were 0.04, –2.17, and –1.24% (Table 4). These results indicated that although the industrial

structure adjustment in China was not obvious (Fig. 4) and was a driving effect in stage 1 (2003–2005, Table 4), it was ultimately effective for mitigating SO₂ discharge. This *adjustment* concept indicated that production resources were reallocated among industrial sectors with different technologies, efficiencies, and profits, thus inducing the changes of output share among different sectors. It was an important source of sustainable growth and a radical approach to transform the developmental pattern (Ren et al. 2012). Thus, with the implementation of the three continuous Five-Year Plans, China's industrial structure gradually transformed from manufacturing industries with heavy pollutant discharges to a new phase with a more reasonable industrial structure. In this new phase, high-tech industries with high added values and low pollutant discharges (such as photovoltaic, electronic, solar, and information industries) rapidly developed. Therefore, the output share of the low discharge group started to continuously increase while that of the high discharge group symmetrically began to decrease from 2011 to 2014. The share of the former rose up from 30.25% in 2011 to 31.90% in 2014, with an annual average increase rate of approximately 0.55% (Fig. 5).

Similarly, industrial structure adjustment also showed a mitigating effect on the NO_x discharge from 2011 to 2014 during which the average annual contribution rate was –1.25% (Table 4). The output share of the low-NO_x discharge

Fig. 4 Change in SO₂ discharge and contributions of its decomposition factors at various stages (the end of the 10th Five-Year Plan (2003–2005), the 11th Five-Year Plan (2005–2010), and the beginning of the 12th Five-Year Plan (2010–2014))

Table 4 Contribution's types and trends at various stages and their average annual contribution (change) rate

Variables	Decomposition effect	SO ₂				NO _x
		Average annual contribution rate (%)				Average annual contribution rate (%)
		Stage 1 ^a	Stage 2 ^a	Stage 3 ^a	2003–2014	2011–2014
Discharge	/	16.45 ^b	−2.68 ^b	−1.61 ^b	0.70 ^b	−6.91 ^b
Output	Output effect	25.77	14.65	7.53	14.33	5.97
Structure	Structure effect	0.04	−2.17	−1.24	−1.16	−1.25
Intensity	Clean production	−10.15	−0.21	−0.39	−2.35	−3.70
	Pollution abatement	0.79	−14.95	−7.51	−10.11	−7.93

Solidus (/) indicates null, and minus sign (−) indicates a negative (mitigating) effect on the two pollutants' discharges

^a Stages 1, 2, and 3 were the end of the 10th Five-Year Plan (2003–2005), the 11th Five-Year Plan (2005–2010), and the beginning of the 12th Five-Year Plan (2010–2014), respectively

^b The average annual change rate of the two discharges

group also started to increase while that of the high-NO_x discharge group symmetrically began to decrease from 2011 to 2014. The share of the former increased from 30.74% in 2011 to 31.67% in 2014, with an annual average increase rate of approximately 0.31% (Fig. 5). These results meant that the contribution of the industrial structural adjustment to mitigate the NO_x discharge was effective from 2011 onward.

Intensity effect (pollution abatement effect and clean production effect)

As shown in Table 3, the intensity effect of the SO₂ discharge had a slight mitigating impact during stage 1 (18.74%). It obviously increased in stages 2 and 3 (75.77 and 31.60%, respectively). The whole mitigating impact was 137.11%. Similarly, the mitigating impact on the NO_x discharge was 34.87% from 2011 to 2014. All the mitigating impacts of the intensity effects were stronger than the structure effects for both SO₂ and NO_x. These results indicated that the reductions

of China's SO₂ and NO_x discharges mainly depended on the intensity effect since it was the overall reflection of technological improvement under the guidelines of various environment laws, regulations, tax policies, and other measures. Taking the investment in pollution control as an example, the intensity effect manifested technological progress' effectiveness of the total government investments used to reduce pollutant discharges (Lei et al. 2012).

The intensity effect was equal to the pollution abatement effect added by the clean production effect ($\Delta Y_I = \Delta Y_A + \Delta Y_C$). Thus, they can be separately analyzed. In most years (except for 2004–2005), the pollution abatement effect had the dominant mitigation impacts on SO₂ and NO_x discharges (Table 3). For stages 1, 2, and 3, the corresponding decomposition results of the pollution abatement effect on SO₂ discharge were 0.23, −14.60, and −5.08 Mt (Fig. 2), with the average annual change rates of 0.79, −14.95, and −7.51% (Table 4), respectively. This result was consistent with Figs. 2, 4, and 5. During 2003–2014, the average annual contribution rate of the pollution abatement effect on mitigating SO₂ discharge was the largest (−10.11%) among the four effects (output, structure, clean production, and pollutant abatement effects, Table 4). Similarly, from 2011 to 2014, the decomposition result of the pollution abatement effect on NO_x discharge was −3.95 Mt (Fig. 2), with an average annual contribution rate of −7.92% (Table 4). This was also consistent with Figs. 2 and 4. The average annual contribution rate was also the largest among the four effects. Thus, the pollution abatement effect was the most important factor for mitigating SO₂ and NO_x discharges in China.

A question is that how the pollution abatement effect could increase SO₂ emissions from 2004 to 2005 which caused a growth rate of 1.01 and an amount of 0.23 Mt from 2003 to 2005 must be answered? This phenomenon could arise from the massive outbreak of the severe acute respiratory syndrome (SARS) virus and the related natural disasters in 2003. In

Fig. 5 Output share change for the high- and low-discharge groups in China (according to the ranking of annual average SO₂ discharge during 2003–2014 or NO_x discharge over 2011–2014. The high-discharge group corresponded to the top half of the sub-sectors, and the low-discharge group to the bottom half of the sub-sectors)

2003, the government had implemented many energy-intensive control measures to combat SARS including related research, development, and management behaviors. Fortunately, the SARS virus was soon under control and people's lives returned to normal. However, due to the lag in policy, these energy-intensive control measures caused the pollution abatement effect to show an opposing increase from 2004 to 2005.

The clean production effect had a mitigating impact on SO₂ and NO_x discharges (Table 3), but it also had an obvious sensitivity. The clean production effect had a promotional (driving) impact on the two pollutant discharges in more years than the pollution abatement effect (Table 3). For stage 1, stage 2, and stage 3, the corresponding decomposition results of the clean production effect on SO₂ discharge were -2.99 , -0.20 , and -0.27 Mt (Fig. 2), and the average annual change rates were -10.15 , -0.21 , and -0.39% , respectively (Table 4). The average annual contribution rate of clean production effect on mitigating SO₂ discharge was the second largest (-2.35%) among the four effects (output, structure, clean production, and pollutant abatement effects; Table 4) from 2003 to 2014. Similarly, from 2011 to 2014, the decomposition result of the clean production effect on NO_x discharge was -1.84 Mt (Fig. 2), with the average annual contribution rate of -3.70% (Table 4). This average annual contribution rate was also the second largest among the four effects. Thus, after the pollution abatement effect, the clean production effect was also an important factor for mitigating SO₂ and NO_x discharges in China.

Different sub-sector comparisons from structural perspective

Based on these results, the contribution of the industrial structure adjustment on mitigating SO₂ and NO_x discharges started to become more obviously effective, especially from 2011 onward. In addition, the industrial SO₂ and NO_x discharges were the sum of all sub-sectors. Therefore, it was essential to decompose the contribution of each sub-sector into the four effects (output, structure, clean production, and pollution abatement). The results are given below.

SO₂

Overall, from 2003 to 2014, the average annual change of China's industrial SO₂ discharge was 10.32×10^4 t, and the effects brought by output, structure, clean production, and pollution abatement were 210.66×10^4 , -17.08×10^4 , -34.58×10^4 , and -148.68×10^4 t, respectively. For all sub-sectors, the average contributions of the four decomposition effects and the total effect on the SO₂ discharge are illustrated in Fig. 6. It can easily be seen that there were 21 industrial sub-sectors with a positive total effect on SO₂ discharge, including

I25 (smelting and pressing of ferrous metals), I26 (smelting and pressing of non-ferrous metals), I24 (manufacture of non-metallic mineral products), and others (Fig. 6b). The total effect of these sectors was 34.75×10^4 t, accounting for 337% of the average change in SO₂ discharge. Inversely, there were 17 industrial sub-sectors with a negative total effect on the SO₂ discharge, including I36 (production and supply of electric power and heat power), I22 (manufacture of chemical fibers), I30 (manufacture of transport equipment), and others (Fig. 6b). The total effect of these sectors was -24.43×10^4 t, accounting for -237% of the average change in the SO₂ discharge.

For the output effect on SO₂ discharge, the main contributing sub-sectors were I36, I24, I25, I26, and I20 (manufacture of raw chemical materials and chemical products); I19 (manufacture of beverages); and I16 (mining of other ores). These seven sub-sectors accounted for 89.99% of the output effect from all sub-sectors from 2003 to 2014 (Fig. 6a; Table 5). Therefore, these seven sub-sectors should be the top sectors to reduce industrial SO₂ discharge. One potential option to reduce industrial SO₂ discharge could be applied based on this result. For example, people could focus on slowing the expansion of these sectors' economic scales or encourage them to restructure similarly to other sectors with less SO₂ discharge.

It should be noteworthy that these sectors had also the top mitigating effects (pollution abatement effect and intensity effect; Table 5). These results indicated these sectors' significance in mitigating SO₂ discharge. In addition, the sub-sectors I11 (manufacture of textiles) and I1 (mining and washing of coal) had also the obvious structure effect and/or clean production effect for mitigating SO₂ discharge (Table 5). Therefore, focus should be placed on these two sectors.

In addition, the effect of clean production technology accounted for 18.87% ($= -34.58 / -183.26$) of the intensity effect and it had the same mitigating effect on SO₂ discharge. However, the sub-sector I25 had an opposite driving effect (Table 5). These results indicated that sector I25 might include some sub-sectors with low clean technology. Similarly, the structure effect had the mitigating effect of 17.08×10^4 t on SO₂ discharge, but the sub-sectors I24, I26, and I20 had the opposite driving effects of 5.54×10^4 , 4.98×10^4 , and 1.73×10^4 t on SO₂ discharge, respectively. The reason could be attributed to the increase of these sectors' output shares (Table S4). Thus, among these sectors (I36, I24, I25, I20, I26, I19, I16, I11, and I1), I20, I24, I25, and I26 should be the focus and should receive priority consideration in designing the related mitigation policies.

NO_x

From 2011 to 2014, the average annual change of China's industrial NO_x discharge was -114.66×10^4 t. The effects of output, structure, clean production, and pollution abatement were 99.06×10^4 , -20.73×10^4 , -61.45×10^4 , and $-$

Fig. 6 The average contributions of the four effects and the total effect on SO₂ discharge from 2003 and 2014 for all sub-sectors (10⁴ t). **a** Four decomposition effects. **b** Total cumulative effect

131.54×10^4 t, respectively. It can also be seen that there were 24 industrial sub-sectors with a positive (driving) effect on NO_x discharge, including I24, I26, I20, and others (Fig. 7b). The total promotional effect of these sectors was 18.21×10^4 t, which accounted for -15.88% of the average change of NO_x discharge. Inversely, there were 14 industrial sub-sectors with a negative (mitigating) effect on NO_x discharge, including I36, I16, and I7 (processing of food from agricultural products) and others (Fig. 7b). The total mitigating effect of these sectors was -132.88×10^4 t, which accounted for 115.88% of the average change of NO_x discharge.

The main contributing sub-sectors of the output effect on NO_x discharge were also I36, I24, I25, I20, I19, I26, and I16. These seven sub-sectors accounted for 96.02% of the output

effect from all sub-sectors from 2011 to 2014 (Fig. 7a; Table 6). Therefore, these seven sub-sectors should also be the top sectors to reduce industrial NO_x discharge. Furthermore, these sub-sectors also had the top mitigating effects (pollution abatement effect, structure effect, or clean production effect; Table 6) on NO_x discharge, which was still similar to SO₂.

In addition, sub-sectors I11 and I7 had the obvious clean production effect or intensity effect for mitigating the NO_x discharge (Table 6). Therefore, the two sectors should also be encouraged. Similarly, the structure effect had a mitigating impact of 20.73×10^4 t on the NO_x discharge, but the sub-sectors I24, I20, and I26 had the opposite driving effects of 10.12×10^4 , 0.97×10^4 , and 0.51×10^4 t on NO_x discharge,

Table 5 The top seven contributing sub-sectors of the decomposition effects on the SO₂ discharge (10⁴ t)

No.	Output effect	Structure effect	Clean production	Pollution abatement	Intensity effect
1	103.49 (I36)	-27.17 (I36)	-11.66 (I24)	-98.83 (I36)	-98.21 (I36)
2	25.44 (I24)	5.54 (I24)	-7.00 (I26)	-14.48 (I24)	-26.15 (I24)
3	19.55 (I25)	4.98 (I26)	-4.65 (I20)	-9.23 (I25)	-12.12 (I20)
4	15.04 (I20)	1.73 (I20)	2.42 (I25)	-7.48 (I20)	-11.27 (I26)
5	12.19 (I26)	-1.15 (I16)	-2.25 (I1)	-4.27 (I26)	-6.81 (I25)
6	8.42 (I19)	-0.95 (I19)	-2.13 (I11)	-2.62 (I19)	-4.34 (I19)
7	5.45 (I16)	-0.90 (I11)	-1.87 (I16)	-1.98 (I16)	-3.85 (I16)
Sum of seven	189.58	-17.92	-27.14	-138.90	-162.75
All sub-sectors	210.66	-17.08	-34.58	-148.68	-183.26
Share of seven	89.99%	104.89%	78.48%	93.42%	88.81%

The effects were sorted by the corresponding absolute value of the size. The contents inside the parentheses were the corresponding industrial numbers, which were consistent with Table 1

Fig. 7 The average contributions of the four effects and the total effect on NO_x discharge from 2011 and 2014 for all sub-sectors (10⁴ t). **a** Four decomposition effects. **b** Total cumulative effect

respectively. The reason could also be attributed to the increase of these sectors' output shares (Table S4). Furthermore, the effect of clean production technology accounted for 31.84% ($= -61.45 / -193.00$) of the intensity effect and had the same mitigating effect on NO_x discharge. However, the sub-sector I20 had the opposite driving effect (Table 6). These results indicated that this sector (I20) might include some sub-sectors with low levels of clean technology. Sectors I24, I16, I26, I19, and I11 also experienced the opposite driving effect of pollution abatement, and sectors I26 and I19 had the opposite driving impact of intensity effect on NO_x discharge (Table 6). Thus, among these sectors (I36, I24, I25, I20, I26, I19, I16, I11, and I7), I11, I16, I19, I20, I24, and I26 should be given priority consideration when designing NO_x mitigation policies.

It should be noted that the sector I36 had an obvious total effect for mitigating the SO₂ discharge (Fig. 6). The effect for NO_x was much more obvious (Fig. 7). The reason could be attributed to the transformation from a coal-dominant electricity generation pattern to more dependence on non-fossil energy such as solar, wind, and biomass energies in China. Through comparing the prior sub-sectors' results for mitigating SO₂ and NO_x discharges, it can be concluded that to simultaneously mitigate the two discharges, sectors I20, I24, and I26 should be given the most priority consideration when designing the related mitigation policies. Then, sectors I11, I16, I19, and I25 should be given the second priority consideration. Last, sectors I1, I7, and I36 should also be given priority consideration or encouraged to develop as soon as

Table 6 The top seven contributing sub-sectors of the decomposition effects on NO_x discharge (10⁴ t)

No.	Output effect	Structure effect	Clean production	Pollution abatement	Intensity effect
1	60.26 (I36)	-23.65 (I36)	-29.97 (I24)	-148.56 (I36)	-167.75 (I36)
2	18.84 (I24)	10.12 (I24)	-19.19 (I36)	8.20 (I24)	-21.77 (I24)
3	6.59 (I25)	-4.93 (I25)	-6.94 (I16)	5.59 (I16)	-2.13 (I20)
4	3.72 (I20)	-2.21 (I19)	-1.26 (I11)	3.10 (I26)	1.92 (I26)
5	2.56 (I19)	0.97 (I20)	-1.17 (I26)	-2.81 (I20)	-1.35 (I16)
6	1.75 (I26)	-0.93 (I16)	-0.79 (I7)	1.36 (I19)	-1.27 (I7)
7	1.40 (I16)	0.51 (I26)	0.68 (I20)	0.78 (I11)	0.73 (I19)
Sum of seven	95.12	-20.11	-58.63	-132.34	-191.61
All sub-sectors	99.06	-20.73	-61.45	-131.54	-193.00
Share of seven (%)	96.02	97.03	95.41	100.61	99.28

The sort orders and the contents inside the parentheses were the same as those in Table 5

possible because of their obvious mitigating effects on the two discharges.

Credibility, novelty, and uncertainty

It was concluded that the LMDI decomposition had some outstanding theoretical properties, including adaptability, ease of use, and the interpretation of results (Ang 1999; Ang and Liu 2001; Ang et al. 2003; Ang 2004; Ang and Liu 2007; Ma and Stern 2008). For example, this decomposition was regarded as perfect since there was no unexplained residual term that other methods may produce (Lyu et al. 2016). Moreover, the pollutant treatment technology and the other two factors have also been recently investigated as the potential drivers of single SO₂ emissions in China from 1995 to 2014 using the LMDI method (Yang et al. 2016). In addition, taking Jiangsu Province as a case, Wang et al. (2017) also used this method to conduct the decomposition and analysis of single SO₂ emissions from the perspective of the whole pollutant treatment process. These studies can somewhat prove the reliability of this LMDI method and the credibility of the results of this paper.

However, all these studies that have been mentioned have not simultaneously investigated the potential driving forces of the two discharges (SO₂ and NO_x) from the perspectives of both the Five-Year Plan and industrial structure. Thus, taking China as a case in this paper, we first completed this work, using the LMDI method. Therefore, this work reflected the innovation significance of this article.

In addition, it should be noteworthy that there are still some uncertainties in this study. For example, the activity data that accounted for the national emission inventories may bring some inherent errors. For example, the varied ratio owed to energy data in 2012 was found to be 30.0% for SO₂ and 16.4% for NO_x (Hong et al. 2017). Moreover, the discharges of SO₂ or NO_x may be mainly distributed in Eastern China (i.e., in the Jingjinji Region (which is made up of Beijing City, Tianjin City, and Hebei Province) because of the more developed economic level in these regions. Therefore, the decomposition analysis of the entirety of China ignores the gap from the different regions. All of these facts mentioned above may induce some errors in the results. However, they cannot affect the overall trend and credibility of these results.

Conclusions and policy implications

Mitigating the discharges of these two pollutants (SO₂ and NO_x) in the air is important to ensuring a cleaner atmospheric environment and better public health. However, few scientists had investigated the potential driving forces of these two discharges from the perspectives of both the Five-Year Plan period and industrial structure. Thus, taking China as a case in this paper, we completed this work through a decomposition

analysis using the LMDI method. The two pollutants' discharges were decomposed into the output effect, structural effect, clean production effect, and pollution abatement effect. The results showed that China's industrial SO₂ discharge increased to 1.14 Mt from 2003 to 2014. The contributions by the four effects were 23.17, −1.88, −3.80, and −16.36 Mt, respectively. Likewise, NO_x discharge increased to −3.44 Mt from 2011 to 2014, and the corresponding contributions by the four effects were 2.97, −0.62, −1.84, and −3.95 Mt. Thus, the output effect (industrial output growth) was always the most prominent driving force for the growth of the two discharges due to rapid industrialization and urbanization in recent years. The average annual contribution rates were 14.33 and 5.97%. Inversely, pollution abatement technology presented the most obvious mitigating effects (−10.11 and −7.92%, respectively). Next were the mitigating effects of clean production technology (−2.35 and −3.7%). The mitigation of the structural effect was the weakest (−1.16 and −1.25%).

From the structural perspective, there were 21 industrial sub-sectors with the positive total effect and 17 sub-sectors with the negative total effect on SO₂ discharge. Meanwhile, seven sub-sectors (I36, I24, I25, I20, I26, I19, and I16) accounted for 89.99% of the total output effect from all sub-sectors from 2003 to 2014. Similarly, there were 24 industrial sub-sectors with the positive total effect and 14 sub-sectors with the negative total effect on NO_x discharge. Nonetheless, the seven sub-sectors accounted for 96.02% of the total output effect from all sub-sectors from 2011 to 2014. For reducing both SO₂ and NO_x discharges, sub-sectors I20, I24, and I26 should be given the most priority consideration since these sub-sectors were the major contributors to the two discharges.

Therefore, based upon these results, some particular strategies and/or policy implications for mitigating the two discharges in China are proposed as follows.

First, the Chinese government should establish a plan to decrease the two discharges that are orientated in the technological discharge reduction direction. For example, the corresponding clean production technologies and pollution abatement technologies should also be greatly improved over the whole progress. These technologies contained the treatment process of pollutants' sources, the reuse of resources, the recycling of waste, and the end-controlling of pollutants, among others.

Next, output effect was mainly responsible for the growth of the two discharges. However, the economic growth should not be greatly inhibited due to the need of a better life from people. Therefore, the utilization efficiencies of all types of resources (contained energies) should be improved while maintaining economic development. In other words, a circular economy should be promoted. For example, those resource-intensive industries with backward technologies and low efficiencies should be gradually phased out.

Then, although the mitigation of the industrial structural effect was the weakest, it could still not be neglected. The reason is that the pollutant reduction policies related to the industrial structure adjustment should be a long-term measure for the two discharges. Thus, only by constantly optimizing the industrial structure can we reduce the two pollutants (SO_2 and NO_x) over a long period of time. This effect is unlikely to occur in the short term or in the traditional industrial pattern.

Last, the reduction-related policies to mitigate both SO_2 and NO_x discharges should focus the sub-sectors of I20, I24, I26, I11, I16, I19, I25, I1, I7, and I36, especially the first three sub-sectors. For example, in the mining and washing of coal (I1), some clean and renewable energies or technologies (such as photovoltaic battery technology and solar thermal power generation technology) should be still continuously promoted to reduce or inhibit the use of coal as much as possible.

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Author contributions JS. J. and DM. X. designed the research. ZH. G., ZY. G., and CD. C. performed it and analyzed the result. JS. J. and ZH. G. wrote the text. All authors read and approved the final manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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