water

MDPI

Article

Multi-Perspectives' Comparisons and Mitigating Implications for the COD and NH_3-N Discharges into the Wastewater from the Industrial Sector of China

Junsong Jia [1,2,*], Huiyong Jian [2,3], Dongming Xie [4], Zhongyu Gu [1,2] and Chundi Chen [5,*]

[1] Key Laboratory of Poyang Lake Wetland and Watershed Research, Ministry of Education, Jiangxi Normal University, Nanchang 330022, China; guzhongyu@jxnu.edu.cn
[2] School of Geography and Environment, Jiangxi Normal University, Nanchang 330022, China; jhygoodjob@jxnu.edu.cn
[3] Graduate School of Jiangxi Normal University, Nanchang 330022, China
[4] Jiangxi Science & Technology Normal University, Nanchang 330013, China; jxstnu_xdm@jxstnu.edu.cn
[5] Chongqing Institute of Green and Intelligent Technology, Chinese Academy of Sciences, Chongqing 400714, China
* Correspondence: jiaaniu@jxnu.edu.cn (J.J.); chenchundi@cigit.ac.cn (C.C.); Fax: +86-791-8812-0440 (J.J.)

Academic Editor: Andreas N. Angelakis
Received: 15 November 2016; Accepted: 7 March 2017; Published: 13 March 2017

Abstract: Taking China as a case study, we analyzed the underlying driving forces of two discharges—chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N)—from both periodic and structural perspectives by the Logarithmic Mean Divisia Index (LMDI) method. Changes in the two discharges were decomposed into three effects: the economic output effect, the industrial structure effect and the discharge intensity effect. The discharge intensity effect could be further decomposed into the cleaner production (technologies') effect and the pollution abatement (technologies') effect. Results showed that the economic output effect was mainly responsible for the growth of the two discharges; the average annual contribution rates were 10.77% and 10.39%, respectively. Inversely, the pollution abatement (technologies') effect presented the most obvious mitigating effects (−9.71% and −9.52%, respectively). Furthermore, the clean production (technologies') effect followed it (−4.36% and −5.22%). So, we found that the discharge intensity effect played a crucial role in the reduction of the two discharges. Then, the mitigation effect of industrial structure adjustment was the weakest (−0.19% and 0.47%). However, we could still not ignore the potential impact of industrial structure optimization for reducing the absolute amount of discharges in the long run. In addition, to simultaneously reduce the COD and NH_3-N discharges, the sub-sectors of "Processing of Food from Agricultural Products (I7)", "Manufacture of Foods (I8)", "Manufacture of Raw Chemical Materials and Chemical Products (I20)", "Manufacture of Non-metallic Mineral Products (I24)" and "Smelting and Pressing of Non-ferrous Metals (I26)" were suggested to be given prior consideration for the design of related mitigation policies. Finally, some particular policy implications were also recommended for reducing the two discharges.

Keywords: multi-perspective; drivers; COD and NH_3-N discharges; mitigating implication; LMDI; China

1. Introduction

Organic carbon, nitrogen and phosphorus have always been considered major water pollutants, but they are attracting increasing attention around the world [1,2]. However, chemical oxygen demand (COD) and ammonia nitrogen (NH_3-N) are often considered the best indicators for preventing or reducing water pollution [3–5]. For example, some scientists have studied the effects of electrochemical oxidation [6–9] and ozone oxidation [10] as well as bioremediation engineering methods [4] on the simultaneous removal of these two indicator pollutants (COD and NH_3-N) from different types of wastewater. Additionally, other scholars have used response surface methodology to analyze the optimal conditions for the removal of the two indicators [11–13] for the following reasons. The COD can, to some extent, reflect the organic carbon content of wastewater [14,15], and NH_3-N can describe the nitrogen content [16]. However, there are no indicators of phosphorus pollution in the relevant databases and the National Controlling Plan of China [17]. Therefore, the above two indicator pollutants (COD and NH_3-N) in China are the focus of this paper. In fact, reducing the discharge of these two pollutants is important for maintaining cleaner aquatic environments.

To realize this goal, it is essential to clarify the relationship between the macroeconomic drivers and the two pollutants and to then identify the main drivers and formulate effective measures to reduce them. Grossman et al. [18] advanced the environmental Kuznets curve (EKC) to explain the relationship between pollution and economic growth, and based on this concept, the discharge of these two pollutants should show an inverted-U shape in response to the rapid development of wealth. However, the inverted-U shape is not the only possible relationship between economic development and the two pollutants [19,20]; in other words, the economy may be not the exclusive driver of their discharge [21,22]. For example, Lei et al. [23] attributed the discharge dynamics of these pollutants (Y) to the three drivers of economic output (G), industrial structure (S) and discharge intensity (I). Here, G refers to the gross domestic product (GDP) from all studied industrial sub-sectors, and S indicates that the different industrial sub-sectors are responsible for different shares of the output and have greatly different impacts on the discharge of the pollutants. I denotes the amount of discharge per unit of GDP, which can, to some extent, reflect the level of technological progress. Moreover, the effect of I can be further divided into the influence of cleaner production (C) and pollution abatement (A), where C indicates the production of the two pollutants per unit of GDP, and A is the ratio of the pollutants being produced. Therefore, C and A can reflect the development of cleaner production technologies (CPT) and pollution abatement technologies (PAT), respectively [23]. The CPT focuses on the management of these pollutants' sources and the reuse of resources during the process of production, whereas PAT focuses on the controlling output of pollution.

Thus, taking China as a case study, we attempt to analyze the impacts of these macroeconomic drivers on the two pollutants (COD and NH_3-N) by using an appropriate model. In the previous literature, two models have commonly been used [24,25]: structural decomposition analysis (SDA) and index decomposition analysis (IDA). The SDA model often requires input–output economic data, while only aggregate data for each industrial category is needed for the IDA model [26–28]. Moreover, SDA can only analyze change between a limited number of years, while IDA can usually analyze change over any time period [24,29], so the IDA model was adopted based on the available data. Additionally, there are many indices available in the IDA model to quantify the impacts of factorial changes on the aggregate industrial sector, such as the Laspeyres index [30], the Paasche index [24], the Arithmetic Mean Divisia Index [31] and the Logarithmic Mean Divisia Index (LMDI) [32–35]. Among these indexes, the LMDI has become the most popular because of its incomparable advantages [36–41]; for example, it has some outstanding advantages in terms of its theoretical foundation (e.g., no unexplained residuals), adaptability and the interpretation of results [42–45]. Therefore, this LMDI (or "IDA-LMDI") model was ultimately chosen. It should be noted that few scientists have studied the drivers of the two indicator discharges (COD or NH_3-N) in China to date from the perspectives of either the planning period or industrial structure, so this work is innovative.

The paper is organized as follows. The LMDI decomposition method and the corresponding data sources are described in Section 2, and the results of the analysis and the related discussion are presented in Section 3. Some conclusions and particular strategies and policy implications for mitigating the discharge of COD and NH_3-N in China, especially in the industrial sector, are proposed in Section 4.

2. Data and Methodology

2.1. Description of the Data

All the economic and pollutant data (COD or NH_3-N) were derived from the China Statistical Yearbook (CSY) and the China Statistical Yearbook on the Environment (CSYE) for the 2004–2015 years. To eliminate the influence of price changes on the raw economic data, we deflated the current prices to 2010 prices using the corresponding price indices, and since the price indices were not available at the industrial sub-sector levels, we instead used the price indices for the entire industrial sector. To a certain extent, this replacement may have resulted in some errors, but it did not affect the overall trend and validity of the results of this study. The amount and share of ancillary activities for exploitation (AAE) were marginal, i.e., the industrial COD or NH_3-N discharges from AAE were close to 0 in most years. Therefore, the industrial AAE was excluded, as were some industries. In the end, 38 industrial sub-sectors were investigated in this study (Table A1).

2.2. The IDA-LMDI Decomposition Model

The IDA-LMDA model has been developed within the energy field but not in environment or water-related fields [42]. Therefore, it is worth discussing the effectiveness of this method for water pollutant parameters. Particularly, the two indicator discharges (COD or NH_3-N) were first expressed as Y in Equation (1). Then, Y was decomposed into A, C, S and G (or I, S and G) [23,46–48].

$$\begin{aligned} Y = \sum_{i=1}^{38} \frac{Y_i}{G} \times G = \sum_{i=1}^{38} \frac{Y_i}{G_i} \times \frac{G_i}{G} \times G &= \sum_{i=1}^{38} \frac{Y_i}{P_i} \times \frac{P_i}{G_i} \times \frac{G_i}{G} \times G \\ &= \sum_{i=1}^{38} A_i \times C_i \times S_i \times G \\ &= \sum_{i=1}^{38} I_i \times S_i \times G \end{aligned} \tag{1}$$

where i is the number of industrial sub-sectors, i.e., 1, 2, . . . , 38; P is the industrial production of the two indicator pollutants; and Y_i, P_i, G_i, A_i, C_i, S_i and I_i are the Y, P, G, A, C, S and I of the i industrial sub-sectors, respectively. The unit of Y is the metric ton (t) and the unit of G is Chinese Yuans (CNY).

Basing the logarithmic differentiation of Equation (1) on time, we get:

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

where $\varphi_i(t) = \frac{A_i \times C_i \times S_i \times G}{Y} = \frac{Y_i}{Y}$.

Integrating Equation (2) over the time interval [0, T], we get:

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

Next, we exponentiate Equation (3):

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

In accordance with the definite integral middle value theorem, Equation (4) can be transformed as follows:

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

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

According to [42], the IDA-LMDI model has the desirable properties of no residual term and aggregation consistency, which allows sub-sector estimates to be consistently aggregated. Correspondingly, the $\varphi_i(t^*)$ weight function could be expressed as:

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

where the logarithmic mean of two positive numbers is:

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

Thus, Equation (5) could be simplified to:

$$\Psi Y_{TOT} = Y_T/Y_0 = \Psi Y_I \times \Psi Y_S \times \Psi Y_G = \Psi Y_A \times \Psi Y_C \times \Psi Y_S \times \Psi Y_G \tag{8}$$

where ΨY_{TOT} means the total multiplicative changes of the discharges from year 0 (Y_0) to T (Y_T). $\Psi Y_\zeta = \exp\left(\sum_{i=1}^{38} \frac{(Y_{i,T}-Y_{i,0})/(\ln Y_{i,T}-\ln Y_{i,0})}{(Y_T-Y_0)/(\ln Y_T-\ln Y_0)} \times \ln \frac{\zeta_{i,T}}{\zeta_{i,0}}\right)$, and ζ denotes I, A, C, S and G.

Equation (8) is the multiplicative formulation of LMDI decomposition for the discharge of COD or NH_3-N in China. The corresponding additive formulation of the LMDI model can be written as follows based on [42]:

$$\Delta Y_{TOT} = Y_T - Y_0 = \Delta Y_I + \Delta Y_S + \Delta Y_G = \Delta Y_A + \Delta Y_C + \Delta Y_S + \Delta Y_G \tag{9}$$

where ΔY_{TOT} means the total additive changes of the discharges from year 0 (Y_0) to T (Y_T). $\Delta Y_\zeta = \sum_{j=1}^{38} \frac{Y_{i,T}-Y_{i,0}}{\ln Y_{i,T}-\ln Y_{i,0}} \times \ln \frac{\zeta_{i,T}}{\zeta_{i,0}}$. The unit of ΔY_ζ is t, but ΨY_ζ in Equation (8) has no unit.

In this paper, all the decompositions were based on [42], and the ΨY_{TOT} and ΔY_{TOT} were decomposed into several different effects associated with the following factors: economic output (ΨY_G and ΔY_G), industrial structure (ΨY_S and ΔY_S), and discharge intensity (ΨY_I and ΔY_I). Moreover, the effects of discharge intensity could be further decomposed into two different effects, namely, the effects of clean production technologies (ΨY_C and ΔY_C) and pollution abatement technologies (ΨY_A and ΔY_A).

3. Results and Discussion

3.1. Comparisons of Various Stages from a Periodic Perspective

It is well known that a plan for national economic and social development has been proposed by the Chinese government every 5 years beginning in 1953, with the exception of 1963–1965, that is known as the "Five-Year Plan" [31]. Moreover, since 1978, China has experienced rapid economic growth [49]; it is the fastest growing country, with a remarkable increase in industrial GDP from 7.47 trillion CNY in 2003 to 22.34 trillion CNY in 2014 and a 10.47% annual average rate of increase (Figure 1a). This growth, coupled with industrialization, urbanization and inadequate investment in a basic pollutant treatment infrastructure, has resulted in widespread water pollution [23]. Therefore, people are increasingly asking whether the country's development is sustainable and when and how its aquatic environments will be improved. For example, according to the 12th Five-Year Plan (2011–2015), the government of China decided to conduct some measures to reduce its annual discharges of COD and NH_3-N by no less than 8% and 10%, respectively, while still maintaining an annual average rate of GDP growth of at least 7% [17]. As a result, the industrial GDP growth rate obviously decreased, especially in 2014 (6.93%, Figure 1a), and correspondingly, the discharges of COD and NH_3-N almost steadily decreased from 2011 to 2014 (COD discharge slightly increased in 2012, Figure 1b), which showed that the government mitigation efforts were starting to be effective. These trends were obviously different from the respective changes during the period 2003–2010; e.g., the discharges of both COD and NH_3-N prominently increased in 2005, but the discharge of NH_3-N sharply decreased in 2006 (Figure 1b).

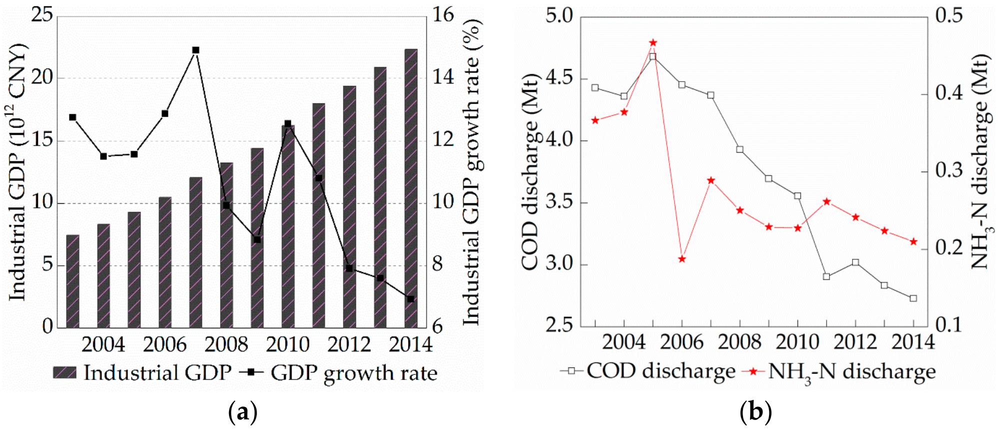

Figure 1. Changes in the industrial GDP (containing the corresponding growth rates) and the dynamics of the two discharges (COD and NH_3-N) during the 2003–2014 period in China. (**a**) GDP and (**b**) Discharges.

To more deeply analyze the potential reasons, we divided the study period (2003–2014) into three stages: 2003–2005, 2005–2010 and 2010–2014. China's COD discharge obviously increased by 0.254 million metric tons (Mt) with a growth rate of 6% in the period 2003–2005 (Figures 1b and 2a; Tables A2 and A3) and then decreased by 1.125 Mt at a rate of −24% in the years 2005–2010 (Figures 1b and 2b; Tables A2 and A3). In the period 2010–2014, it decreased again by 0.828 Mt at a rate of −23% (Figures 1b and 2c; Tables A2 and A3). Overall, COD discharge exhibited an overall decreasing trend (Figure 1b); the amount and rate of change were −1.698 Mt and −38%, respectively (Tables A2 and A3). Similarly, the discharge of NH_3-N in China increased by 0.100 Mt, with an overall growth rate of 27% during the 2003–2005 period (Figures 1b and 2d; Tables A2 and A3). It then decreased by 0.239 Mt at an overall rate of change of −51% in the period 2005–2010 (Figures 1b and 2e; Tables A2 and A3), and in the years 2010–2014, it decreased again by 0.018 Mt at a rate of −8% (Figures 1b and 2f; Tables A2 and A3). Overall, the discharge of NH_3-N in China showed a decreasing trend (Figure 1b); the amount and rate of change were −0.157 Mt and −43%, respectively (Tables A2 and A3). A major difference was apparent in the second stage (2005–2010), when the discharge of NH_3-N fluctuated more drastically while decreasing overall, but the discharge of COD steadily decreased.

Here, the contributions of various factors to the changes in the discharge of the two pollutants are discussed. "Contributions" refer to the proportion of the change in discharge caused by each factor at time T (i.e., the additive decomposition result of each factor) compared to the total discharge at time 0 (Table 1). For the period 2003–2014, the contributions of the factors mitigating COD discharge in China, ranked from high to low, were the pollution abatement effect (−106.81%), the clean production effect (−47.92%), and the industrial structure effect (−2.07%), while the only promoting factor was the economic output effect (118.44%). The promotion effect (118.44%) was less than the combined effect of the mitigating factors (−106.81% − 47.92% − 2.07% = −156.80%), which caused a 38.36% decrease in the total COD discharge in the 2003–2014 period (Table 2). Similarly, the factors mitigating NH_3-N discharge were the pollution abatement effect (−104.77%) and the clean production effect (−57.41%), while the promoting factors were the economic output effect (114.28%) and the industrial structure effect (5.17%). However, the combined influence of the promotion effects (114.28% + 5.17% = 119.45%) was less than the influence of the mitigating effects (−104.77% − 57.41% = −162.18%), which caused an obvious 42.73% decrease in NH_3-N discharge during the 2003–2014 period (Table 1).

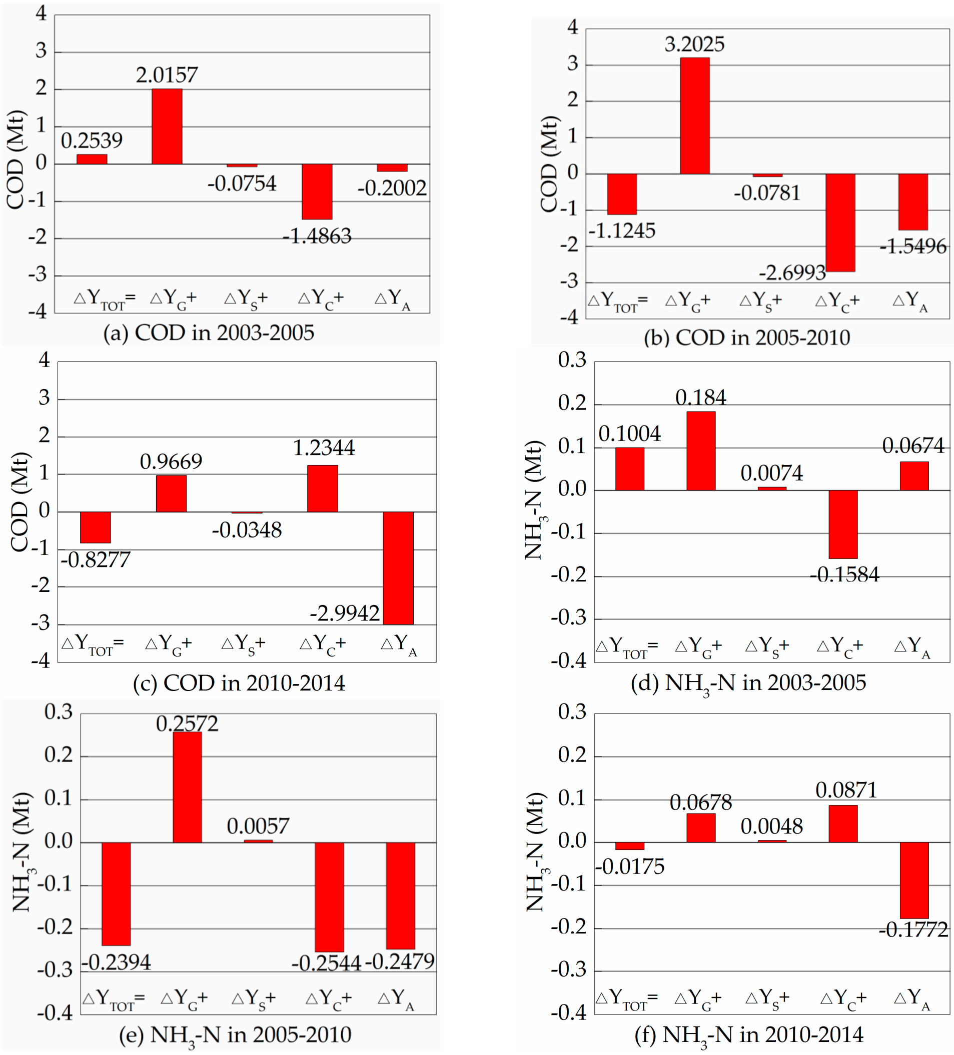

Figure 2. Additive decomposition of the changes in COD and NH_3-N discharge in China in the three "Five-Year Plan" periods (ΔY_{TOT}, ΔY_A, ΔY_C, ΔY_S and ΔY_G denote the total changes in the discharges of the two pollutants and the effects of pollution abatement, clean production, industrial structure and economic output, respectively). (**a**) COD in 2003–2005; (**b**) COD in 2005–2010; (**c**) COD in 2010–2014; (**d**) NH_3-N in 2003–2005; (**e**) NH_3-N in 2005–2010; (**f**) NH_3-N in 2010–2014.

Table 1. Contributions of various factors to the changes in COD and NH_3-N discharge (unit: %).

Period	COD					NH_3-N				
	ΔY_{TOT}	ΔY_G	ΔY_S	ΔY_C	ΔY_A	ΔY_{TOT}	ΔY_G	ΔY_S	ΔY_C	ΔY_A
2003–2004	−1.52	34.98	−0.42	−33.93	−2.15	2.95	35.93	−0.65	−32.59	0.26
2004–2005	7.37	9.39	−1.66	1.85	−2.20	23.75	10.04	2.45	−5.49	16.75
2005–2006	−4.92	18.99	−1.68	−17.55	−4.68	−24.08	16.97	−0.67	−17.55	−22.83
2006–2007	−1.87	16.77	−0.19	−4.57	−13.87	−18.46	15.26	0.83	−12.15	−22.40
2007–2008	−10.03	14.14	−0.37	−13.49	−10.32	−13.34	13.86	0.20	−15.68	−11.72
2008–2009	−5.97	8.49	1.11	−12.69	−2.88	−8.60	8.35	0.64	−11.38	−6.20
2009–2010	−3.75	18.37	−0.75	−15.73	−5.64	−0.64	18.56	0.23	−16.10	−3.33
2010–2011	−18.38	9.91	0.72	64.66	−93.66	15.02	11.97	2.45	90.15	−89.54
2011–2012	3.98	7.62	0.20	−10.41	6.57	−7.66	7.30	0.97	−13.55	−2.38
2012–2013	−6.15	8.27	−0.27	25.78	−39.93	−7.24	8.22	0.42	37.10	−52.99
2013–2014	−3.66	3.93	−2.18	−44.99	39.58	−6.32	3.85	−0.89	−65.83	56.55
2003–2005	5.73	45.49	−1.70	−33.54	−4.52	27.40	50.21	2.02	−43.21	18.39
2005–2010	−24.02	68.41	−1.67	−57.66	−33.10	−51.28	55.08	1.22	−54.49	−53.09
2010–2014	−23.27	27.19	−0.98	34.71	−84.18	−7.71	29.81	2.09	38.30	−77.91
2003–2014	−38.36	118.44	−2.07	−47.92	−106.81	−42.72	114.28	5.17	−57.41	−104.77

Note: "−" denotes a negative (mitigating) contribution (effect) to COD or NH_3-N discharge.

Table 2. Average annual contribution rates at various stages and for the entire study period (%).

Variable	Effect	COD				NH_3-N			
		Stage 1 [a]	Stage 2 [a]	Stage 3 [a]	Whole	Stage 1 [a]	Stage 2 [a]	Stage 3 [a]	Whole
Discharge	/	2.865 [b]	−4.804 [b]	−5.818 [b]	−3.487 [b]	13.7 [b]	−10.256 [b]	−1.928 [b]	−3.884 [b]
Output	G	22.747	13.681	6.796	10.767	25.106	11.016	7.452	10.389
Structure	S	−0.851	−0.334	−0.245	−0.188	1.008	0.244	0.523	0.47
Intensity	C	−16.772	−11.532	8.676	−4.356	−21.607	−10.897	9.576	−5.219
	A	−2.259	−6.62	−21.046	−9.71	9.193	−10.619	−19.478	−9.524

Notes: [a] Stages 1, 2, and 3 were the periods 2003–2005, 2005–2010 and 2010–2014, respectively; [b] indicates the average annual rate of change of the two discharges; "/" represents a null values.

3.1.1. Output Effect

To smooth the short-term volatile effects of various factors [31,42], the cumulative decomposition results were converted from the multiplicative decomposition results in Table A2, listed in Table A4 and depicted in Figure 3. The average annual contributions and the trends of the changes in each effect at different stages are shown in Figure 4 and Table 2, respectively.

It was apparent that only economic output always had a positive effect on the discharge of the two pollutants, and it trended sharply upward during the period 2003–2014 (ΨY_G in Figure 3), which is consistent with the results in Figure 4 and Table 2. It can be seen that the dominant factor influencing the increase in the two pollutants was the gross output expansion (Figure 4).

The additive decomposition effect of economic output on the discharge of COD was 2.016 Mt in the years 2003–2005 (Figure 2a), indicating that economic output was the largest driver of COD growth during the period 2003–2005, and in the years 2005–2010 and 2010–2014, the decomposition effects were 3.203 and 0.967 Mt (Figure 2b,c), respectively. In total, the effect of economic output made the greatest contribution to the total annual rate of COD discharge (10.767%) (Table 2), and for each of the three stages, the average annual contribution rates were 22.747%, 13.681% and 6.796%, respectively (Table 2). Simply stated, the growth in economic output growth was always the most prominent factor driving the increase in COD discharge.

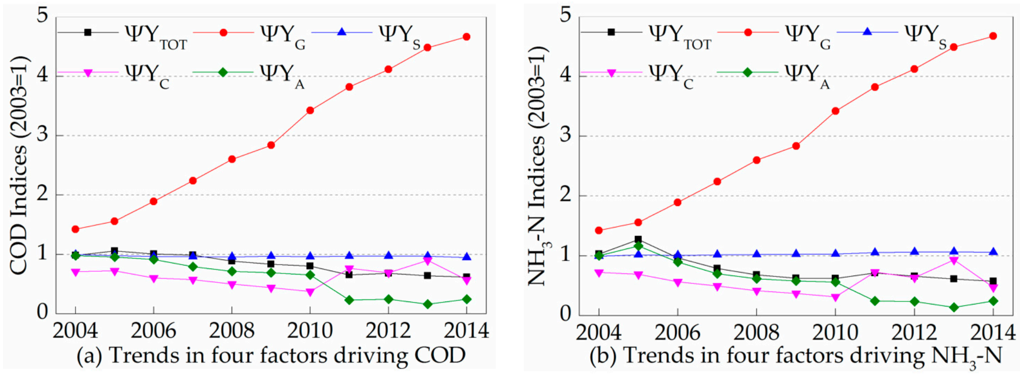

Figure 3. Trends in the cumulative decomposition of the indices of COD and NH_3-N discharge. ΨY_{TOT}, ΨY_A, ΨY_C, ΨY_S and ΨY_G denote the total change and the effects of pollution abatement, clean production, industrial structure and economic output, respectively, on the discharge of the two pollutants. (**a**) Trends in four factors driving COD and (**b**) trends in four factors driving NH_3-N.

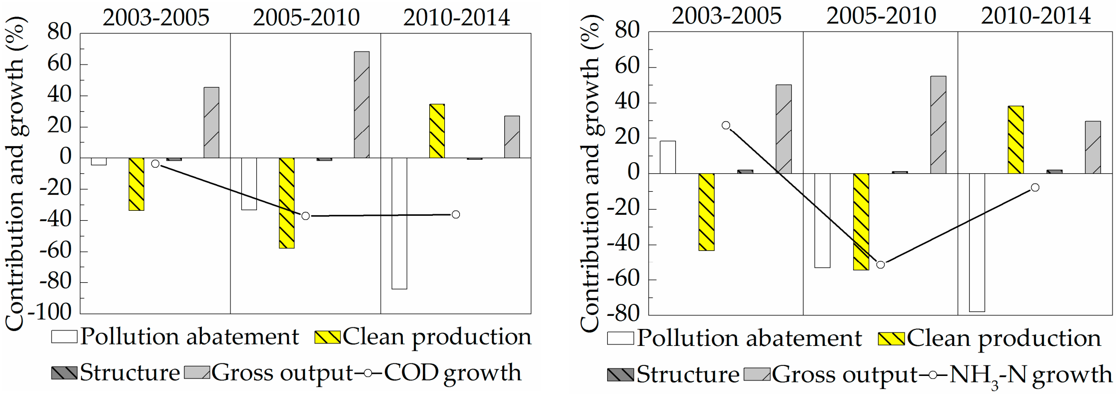

Figure 4. The growth in the discharge of the two pollutants and the contributions of their corresponding decomposition factors at three stages (2003–2005, 2005–2010 and 2010–2014). (**a**) COD and (**b**) NH_3-N.

Similarly, the additive decomposition effect of economic output on NH_3-N discharge was 0.184 Mt in the years 2003–2005 (Figure 2d), and in the periods 2005–2010 and 2010–2014, the effects were 0.257 and 0.068 Mt (Figure 2e,f), respectively. Moreover, the effect of economic output on the annual rate of NH_3-N discharge (10.389%) made a greater contribution than the other factors (Table 2), and during the three stages, the corresponding average annual contribution rates were 25.106%, 11.016% and 7.452%, respectively (Table 2). Additionally, these results mean that the growth in economic output was always the most prominent factor driving the growth in NH_3-N discharge.

3.1.2. Structure Effect

Similar to some previous studies [32,34], we also considered industrial structural adjustment to be an important factor lowering the discharge of pollutants; indeed, it had an overall mitigating effect on COD discharge during the period 2003–2014. For example, the average annual contribution rate of industrial structure to COD discharge was −0.188% (Table 2), and in the three stages, the corresponding average annual contribution rates were −0.851%, −0.334%, and −0.245%, respectively (Table 2). This regularity indicated that the industrial structure adjustment in China effectively mitigated COD discharge (Figure 4).

However, the effect of industrial structure adjustment on NH_3-N discharge was inverted during the period 2003–2014; the average annual contribution rate was 0.470% (Table 2), and in the three stages, the corresponding average annual contribution rates were 1.008%, 0.244%, and 0.523%, respectively (Table 2), indicating that the industrial structure adjustment did not effectively mitigate NH_3-N discharge in China (Figure 4). Therefore, to some extent, the effect of the industrial structure adjustment efficiently mitigated the discharge of some pollutants, such as COD, into the water, but it might inefficiently mitigate the discharge of some other pollutants, such as NH_3-N. Therefore, we should more deeply examine the effect of industrial structure from the perspective of different sub-sectors (the results are presented in Section 3.2).

3.1.3. Intensity Effects (Pollution Abatement Effect and Clean Production Effect)

Overall, the mitigation impacts of the intensity effects on the discharge of both COD and NH_3-N were stronger than those of the structural effects (Figures 2–4; Tables 1 and 2). These results indicated that the reductions in COD and NH_3-N discharges in China should mainly depend on the utilization and improvement of intensity effects, especially in industrial sectors, because the intensity effect reflected the overall technological improvement under the guidelines of various environment laws, regulations, tax policies and other measures [23].

As recommended by Lei et al. [26], the intensity effect was equal to the pollution abatement effect plus the clean production effect ($\Delta Y_I = \Delta Y_A + \Delta Y_C$), so we considered them separately. In most years, the pollution abatement effect had the dominant mitigation impact on the discharge of COD and NH_3-N (Table 1). The largest average annual contribution to the rate of COD discharge (−9.710%, Table 2) came from the pollution abatement effect; in the three stages, the average annual contribution rates were −2.259%, −6.620% and −21.046%, respectively (Table 2). The corresponding decreases in COD discharge due to pollution abatement were −0.200, −1.550 and −2.994 Mt, respectively (Figure 2). Similarly, the average annual contribution of the pollution abatement effect to the rate of NH_3-N discharge was also the largest (−9.524%, Table 2), and in the three stages, the average annual contribution rates were 9.193%, −10.619% and −19.478%, respectively (Table 2). The corresponding reductions in COD discharge due to the pollution abatement effect were 0.067, −0.248 and −0.177 Mt, respectively (Figure 2). Thus, the pollution abatement effect was the most important factor mitigating water pollution due to reductions in the discharges of COD and NH_3-N in China.

In terms of the clean production effect, it also had an overall mitigation impact on the discharge of COD and NH_3-N (Table 1), but the average annual contribution of the clean production effect on the COD discharge rate was the second largest (−4.356%) during the period 2003–2014 (Table 2). In the three stages, the corresponding declines in COD discharge due to the clean production effect were −1.486, −2.699 and 1.234 Mt with average annual contribution rates of −16.772%, −11.532% and 8.676%, respectively (Figure 2 and Table 2). Similarly, the average annual contribution rate of the clean production effect to the mitigation of NH_3-N discharge was also the second largest (−5.219%, Table 2). From stage 1 to stage 3, the corresponding declines in NH_3-N discharge due to the clean production effect were −0.158, −0.254 and 0.087 Mt with average annual contribution rates of −21.607%, −10.897% and 9.576%, respectively (Figure 2 and Table 2). Thus, we could say that after the pollution abatement effect, the clean production effect was the next most important factor mitigating the discharge of COD and NH_3-N in China.

3.2. Comparisons of Different Sub-Sectors from a Structural Perspective

As mentioned above, there were 38 industrial sub-sectors, so it was essential for us to separate the contribution of each sub-sector to the four effects (economic output, industrial structure, clean production and pollution abatement) based on the suggestion in Section 3.1.2, and the corresponding results were as follows. Figure 5 shows the contributions of the four decomposition effects and their total effect on the two pollutants (COD and NH_3-N) for all 38 sub-sectors. The top ten sub-sectors contributing to the discharge of COD and NH_3-N from the perspective of the different decomposition effects are shown in Tables 3 and 4, respectively. The changes in the contributions of the economic output of some special sub-sectors from 2003 to 2014 are shown in Table 5.

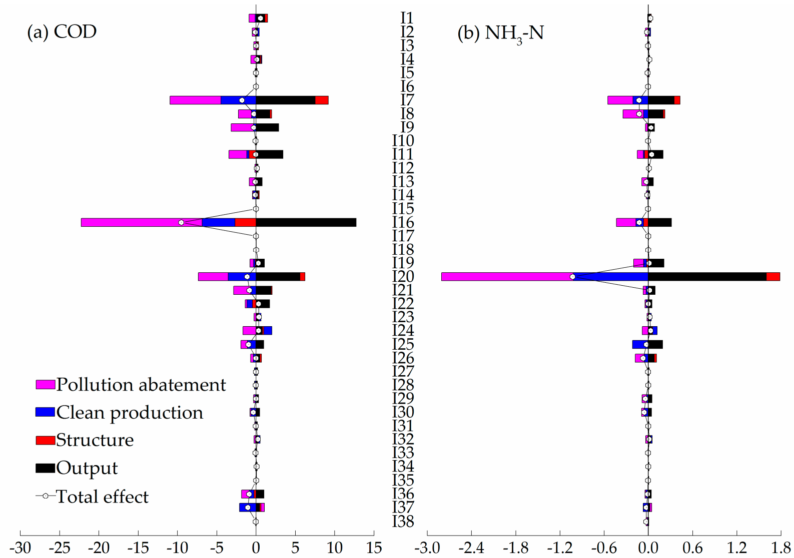

Figure 5. The contributions of the four effects and the corresponding total effect on the two discharges from all 38 sub-sectors during the period 2003–2014 (10^4 t). (**a**) COD and (**b**) NH_3-N.

Table 3. The top ten sub-sectors contributing to COD discharge by their different effects (10^4 t).

No.	Output Effect	Structure Effect	Clean Production	Pollution Abatement	Intensity Effect
1	12.72 (I16)	−2.68 (I16)	−4.48 (I7)	−15.39 (I16)	−19.57 (I16)
2	7.50 (I7)	1.67 (I7)	−4.18 (I16)	−6.48 (I7)	−10.96 (I7)
3	5.57 (I20)	−0.91 (I11)	−3.54 (I20)	−3.81 (I20)	−7.35 (I20)
4	3.41 (I11)	0.64 (I20)	−2.11 (I37)	−2.81 (I9)	−3.18 (I9)
5	2.87 (I9)	−0.46 (I22)	−1.08 (I25)	−2.28 (I11)	−2.88 (I21)
6	1.92 (I21)	0.34 (I1)	1.03 (I24)	−2.17 (I21)	−2.56 (I11)
7	1.74 (I8)	−0.26 (I36)	−0.71 (I21)	−1.69 (I24)	−2.25 (I8)
8	1.71 (I22)	0.22 (I8)	−0.70 (I22)	−1.66 (I8)	−1.90 (I25)
9	1.13 (I1)	0.20 (I26)	−0.64 (I30)	−0.98 (I36)	−1.66 (I37)
10	1.05 (I19)	0.17 (I24)	−0.62 (I36)	−0.82 (I25)	−1.60 (I36)
Sum of ten	39.62	−1.07	−17.03	−38.09	−53.90
All subsectors	47.67	−0.83	−19.29	−42.99	−62.28
Share of ten	83.12%	128.64%	88.30%	88.61%	86.55%

Note: The orders were sorted by their corresponding absolute value; the values in parentheses are the corresponding industrial numbers, which are consistent with those in Table A1.

Table 4. The top ten sub-sectors contributing to NH_3-N discharge by their different effects (10^4 t).

No.	Output Effect	Structure Effect	Clean Production	Pollution Abatement	Intensity Effect
1	1.60 (I20)	0.18 (I20)	−1.02 (I20)	−1.79 (I20)	−2.81 (I20)
2	0.35 (I7)	0.08 (I7)	−0.21 (I7)	−0.34 (I7)	−0.55 (I7)
3	0.31 (I16)	−0.07 (I16)	−0.21 (I25)	−0.28 (I8)	−0.37 (I16)
4	0.21 (I19)	−0.05 (I11)	−0.10 (I16)	−0.27 (I16)	−0.35 (I8)
5	0.20 (I11)	0.03 (I26)	−0.07 (I37)	−0.13 (I19)	−0.20 (I25)
6	0.20 (I8)	0.03 (I8)	−0.07 (I8)	−0.12 (I26)	−0.18 (I26)
7	0.19 (I25)	−0.02 (I19)	0.06 (I24)	−0.08 (I24)	−0.18 (I19)
8	0.09 (I21)	−0.01 (I22)	−0.06 (I30)	−0.08 (I11)	−0.10 (I11)
9	0.08 (I9)	−0.01 (I36)	−0.06 (I26)	−0.07 (I13)	−0.09 (I30)
10	0.08 (I26)	0.01 (I24)	−0.04 (I19)	−0.06 (I29)	−0.09 (I29)
Sum of ten	3.31	0.16	−1.77	−3.24	−4.91
All subsectors	3.81	0.17	−1.91	−3.49	−5.40
Share of ten	86.94%	95.29%	92.63%	92.69%	90.84%

Table 5. The increase in the share of the output of I1, I7, I8, I20, I24 and I26 from 2003 to 2014 (%).

No.	Sector	2003	2014
I1	Mining and Washing of Coal	1.73	2.75
I7	Processing of Food from Agricultural Products	4.09	5.77
I8	Manufacture of Foods	1.51	1.85
I20	Manufacture of Raw Chemical Materials and Chemical Products	6.30	7.53
I24	Manufacture of Non-metallic Mineral Products	3.71	5.20
I26	Smelting and Pressing of Non-ferrous Metals	2.47	4.65

3.2.1. COD

For the period 2003–2014 overall, the average annual change in the industrial COD discharge in China was -15.44×10^4 t, and the effects of economic output, industrial structure, clean production and pollution abatement were -42.99×10^4, -19.29×10^4, -0.83×10^4 and 47.67×10^4 t, respectively (Table A3). Thus, there were twelve industrial sub-sectors that had a combined positive effect on the discharge of COD, e.g., "Mining and Washing of Coal (I1)", "Manufacture of Rubber and Plastics (I23)", "Manufacture of Chemical Fibers (I22)", etc. (Figure 5a). The total effect of these sectors could be calculated as 2.34×10^4 t, which accounts for -15.2% of the change in COD discharge. Conversely, there were twenty-six industrial sub-sectors with a total negative effect on COD discharge, e.g., "Manufacture of Paper and Paper Products (I16)", "Processing of Food from Agricultural Products (I7)", etc. (Figure 5a). The total effect of these sectors was -17.78×10^4 t, accounting for 115.2% of the change in COD discharge.

In terms of the effect of economic output on the discharge of COD, the main contributing sub-sectors were I16, I7, "Manufacture of Raw Chemical Materials and Chemical Products (I20)", "Manufacture of Textiles (I11)", "Manufacture of Beverages (I9)", "Manufacture of Medicines (I21)", "Manufacture of Foods (I8)", I22, I1 and "Processing of Petroleum, Coking, and the Processing of Nuclear Fuel (I19)". These ten sub-sectors accounted for 83.12% of the output effect from all sub-sectors over the period 2003–2014 (Figure 5a; Table 3) and should therefore be the top sectors targeted for reducing industrial COD discharge. One potential option based on this result could be to attempt to slow the expansion of the economic scale of these sub-sectors or to encourage them to convert to other sub-sectors with less COD discharge. It should be noted that these sub-sectors (except I19) also exerted the greatest mitigation effects (pollution abatement or industrial structure or clean production effects, Table 3), further indicating their significance for mitigating COD discharge. In addition, the sub-sectors "Manufacture of Non-metallic Mineral Products (I24)", "Smelting and Pressing of Ferrous Metals (I25)", "Manufacture of Transport Equipment (I30)", "Production and Supply of Electric Power and Heat Power (I36)" and "Production and Supply of Gas (I37)" also had obvious clean production, pollution abatement or intensity effects on COD discharge mitigation (Table 3), therefore much attention should be paid to these five sub-sectors.

The effect of clean production technology accounted for 30.97% ($= -19.29/-62.28$) of the intensity effect, which mitigated COD discharge. However, the I24 sub-sector had an opposite effect (Table 3), indicating that it might include some sub-sectors lacking clean technology. Similarly, the structure effect mitigated 0.83×10^4 t of COD discharge, but the sub-sectors I7, I20, I1, I8, "Smelting and Pressing of Non-ferrous Metals (I26)" and I24 had the opposite impacts of 1.67×10^4, 0.64×10^4, 0.34×10^4, 0.22×10^4, 0.20×10^4 and 0.17×10^4 t of COD discharge, respectively. This fact could be attributed to the increases in the output shares of these sectors (Table 5), so the I1, I7, I8, I20, I24, I25 and I26 sub-sectors are extremely important and should be considered when designing mitigation policies.

3.2.2. NH_3-N

During the period 2003–2014, the average annual change in the discharge of industrial NH_3-N in China was -1.42×10^4 t, and the four effects due to economic output, industrial structure, clean production and pollution abatement were 3.81×10^4, 0.17×10^4, -1.91×10^4 and -3.49×10^4 t, respectively (Table A3). Similarly, there were nineteen industrial sub-sectors with positive (driving) effects on NH_3-N discharge, e.g., I11, I9, I24, etc. (Figure 5b). The total promotional effect of these sectors was 0.26×10^4 t, accounting for −18.19% of the change in NH_3-N discharge. Conversely, there were also nineteen industrial sub-sectors with negative (mitigation) impacts on NH_3-N discharge, e.g., I20, I7, I8, etc. (Figure 5b), and the total mitigating effect of these sectors was -1.68×10^4 t, accounting for 118.19% of the change in NH_3-N discharge. The main sub-sectors contributing to the effect of economic output on NH_3-N discharge were I20, I7, I16, I19, I11, I8, I25, I21, I9 and I26, and they accounted for 86.94% of the output effect of all sub-sectors during the period 2003–2014 (Figure 5b; Table 4). Therefore, these ten sub-sectors should also be priorities for reducing industrial NH_3-N discharge. Similarly, these sub-sectors (except I21 and I9) also had the top mitigation effects (pollution abatement or industrial structure or clean production effects, Table 4) on the NH_3-N discharge, and the sub-sectors I22, I36, I37, I30, "Manufacture of Leather, Fur, Feather and Related Products (I13)" and "Manufacture of Special Purpose Machinery (I29)" had obvious industrial structure, clean production, pollution abatement or intensity mitigation effects on NH_3-N discharge (Table 4). Therefore, these six sectors should also be continuously encouraged.

Similarly, the industrial structure effects of the sub-sectors I20, I7, I26, I8 and I24 mitigated 0.18×10^4, 0.08×10^4, 0.03×10^4, 0.03×10^4 and 0.01×10^4 t of NH_3-N discharge, respectively, which could be due to increases in the output shares of these sectors (Table 5). Additionally, the effect of clean production technology accounted for 35.37% (= −1.91/−5.40) of the intensity effect, which mitigated NH_3-N discharge, but the sub-sector I24 had an opposite driving effect (Table 4). Thus, similar to COD, I7, I8, I20, I24 and I26 should receive attention and prior consideration in designing NH_3-N mitigation policies. In addition, it should be noted that sector I16 had an obvious overall mitigation effect on COD discharge, and sector I20 had an obvious overall mitigation effect on NH_3-N discharge (Figure 5). The reason could be due to the dramatic improvement in the production pattern of the two sub-sectors compared to previous energy-intensive and high pollution-emitting modes in China.

By comparing prior COD and NH_3-N discharges from sub-sectors, we could conclude that, because they simultaneously mitigate both the COD and NH_3-N, sectors I7, I8, I20, I24 and I26 should be given priority when designing mitigation policies. The sectors I1, I9, I11, I16, I19, I21, I22 and I25 should be given second priority because of their powerful driving effects on the discharges of the two pollutants due to the growth in outputs. Finally, the I13, I29, I30, I36 and I37 sectors should also be given prior consideration, or their development should be encouraged because of their obvious mitigation effects. Additionally, we could also speculate that, the obtained results and conclusions should be rich and reliable by still using the LMDI method when the data of phosphorus and some bacterial indicators such as the index of coliform organisms were available. However, there were still some detailed problems for which good answers could not be obtained by using only the LMDI: Why were the clean production effects positive for both COD and NH_3-N in the period 2010–2014? Were there any specific reasons for these increases of COD in 2012 and NH_3-N in 2011? These problems may be explained from the relative theories of specialized economic sciences, which are also the focus of our research direction in the future.

4. Conclusions and Implications

During the period 2003–2014, China's industrial COD discharge decreased by 1.698 Mt, and the contributions of the economic output effect, industrial structural effect, clean production effect and pollution abatement effect were 5.244, −0.092, −2.122 and −4.729 Mt, respectively. Likewise, industrial NH_3-N discharge decreased by 0.157 Mt, and the corresponding contributions of the four effects were 0.419, 0.019, −0.210 and −0.384 Mt, respectively. These results indicated that the growth in economic output was always the most prominent driver of the changes of both the COD and NH_3-N discharges. The average annual contribution rates were 10.77% for COD and 10.39% for NH_3-N, respectively. However, pollution abatement (technology) presented the most obvious mitigation effects, and the corresponding average annual contribution rates were −9.71% for COD and −9.52%

for NH_3-N. The impacts of clean production (technology) followed, and corresponding average annual contribution rates were −4.36% for COD and −5.22% for NH_3-N. Therefore, the intensity effect, which was composed of the pollution abatement effect and the clean production effect, played a crucial role in reducing COD and NH_3-N. The industrial structure effect played a minor role in the changes in the two discharges; the average annual contribution rates of the industrial structure effect on the COD and NH_3-N discharges were −0.19% and 0.47%, respectively. The sectors I7, I8, I20, I24 and I26 should be given the highest priority when designing mitigation policies to simultaneously reduce the discharge of both COD and NH_3-N, and the sectors I1, I9, I11, I16, I19, I21, I22 and I25 should be the second priority. In addition, the sectors I13, I29, I30, I36 and I37 should also be given prior consideration or be encouraged to develop as soon as possible due to their obvious mitigation effects.

Therefore, the Chinese government must seek a trade-off between economic development and pollutant discharge reduction; discharge-reduction policies should gradually counteract the economic output effect by activating structural and technology effects. For example, a circular economy should be promoted so that the total consumption of raw materials and fossil fuels and the corresponding discharge of pollutants can be minimized. Second, the government should pay more attention to improving corresponding clean production and pollution abatement technologies. For example, some regulatory policy instruments (i.e., discharge reduction liability, discharge audits, and discharge rights trading) should be more aggressively implemented to encourage industrial enterprises to improve their resource use efficiency and pollutant discharge performance. Third, adjusting the industrial structure should also be the focus of pollutant discharge reduction policy, especially in the sub-sectors of I1, I7, I8, I9, I11, I13, I16, I19, I20, I21, I22, I24, I25, I26, I29, I30, I36 and I37. For example, in the "Mining and Washing of Coal (I1)" sector, some advanced clean and renewable energy technologies, such as photovoltaic batteries and solar thermal power generation, should continue to be promoted to reduce or inhibit the use of coal as much as possible.

Acknowledgments: We thank the three anonymous reviewers for providing helpful comments and suggestions. We are also grateful for the financial support provided by Chinese National Science Foundation (41001383, 71473113, 31360120, 51408584), Natural Science Foundation of Jiangxi (20151BAB203040) and Scientific or Technological Research Project of Jiangxi's Education Department (GJJ14266).

Author Contributions: Junsong Jia and Chundi Chen designed the research; Huiyong Jian, Dongming Xie and Zhongyu Gu performed it and analyzed the result; Junsong Jia and Huiyong Jian wrote the text. All authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Classification of industrial sub-sectors studied in this paper and their respective GDP (10^{12} CNY), COD (10^4 t) and NH_3-N (10^4 t) during the period 2003–2014.

No.	Sector	GDP			COD			NH_3-N		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
I1	Mining and Washing of Coal	3.10	0.35	1.76	12.4	5.3	8.8	0.57	0.10	0.34
I2	Extraction of Petroleum and Natural Gas	1.19	0.48	0.93	3.3	1.0	1.9	0.24	0.05	0.14
I3	Mining and Processing of Ferrous Metal Ores	0.88	0.05	0.44	1.5	0.8	1.1	0.18	0.02	0.06
I4	Mining and Processing of Non-Ferrous Metal Ores	0.55	0.08	0.32	6.0	3.2	4.4	0.26	0.02	0.14
I5	Mining and Processing of Nonmetal Ores	0.46	0.07	0.24	2.0	0.6	0.9	0.16	0.01	0.04
I6	Mining of Other Ores	0.00	0.00	0.00	0.1	0.0	0.1	0.01	0.00	0.00
I7	Processing of Food from Agricultural Products	5.51	0.83	2.95	67.7	44.1	55.6	4.93	1.88	2.54
I8	Manufacture of Foods	1.77	0.31	0.95	15.5	10.9	12.4	2.57	0.66	1.28
I9	Manufacture of Beverages	1.42	0.30	0.80	25.1	18.7	21.6	1.06	0.39	0.77
I10	Manufacture of Tobacco	0.78	0.31	0.52	0.9	0.2	0.4	0.03	0.01	0.02
I11	Manufacture of Textile	3.31	1.06	2.33	34.5	23.9	29.1	2.02	1.17	1.64
I12	Manufacture of Textile Wearing Apparel, Footware and Caps	1.82	0.46	1.07	2.1	0.8	1.6	0.17	0.04	0.11
I13	Manufacture of Leather, Fur, Feather and Related Products	1.20	0.30	0.70	7.5	4.9	6.4	0.86	0.37	0.64
I14	Processing of Timber, Manufacture of Wood, Bamboo, Rattan, Palm, and Straw Products	1.15	0.13	0.59	3.5	1.1	1.9	0.19	0.03	0.07
I15	Manufacture of Furniture	0.63	0.10	0.35	0.5	0.1	0.2	0.03	0.00	0.01
I16	Manufacture of Paper and Paper Products	1.20	0.34	0.83	159.7	47.8	112.1	4.14	1.63	2.73
I17	Printing, Reproduction of Recording Media	0.59	0.14	0.31	0.5	0.2	0.2	0.10	0.01	0.02
I18	Manufacture of Articles For Culture, Education and Sport	1.29	0.13	0.45	0.2	0.1	0.1	0.02	0.00	0.01
I19	Processing of Petroleum, Coking, Processing of Nuclear Fuel	3.64	0.90	2.45	9.0	6.1	7.7	1.63	0.73	1.25
I20	Manufacture of Raw Chemical Materials and Chemical Products	7.19	1.28	4.05	56.9	3.3	40.4	22.0	6.65	11.88
I21	Manufacture of Medicines	2.02	0.39	1.02	18.8	9.6	11.9	0.94	0.51	0.73
I22	Manufacture of Chemical Fibers	0.65	0.20	0.45	15.7	9.0	12.2	0.48	0.23	0.38
I23	Manufacture of Rubber & Plastics	2.59	0.59	1.60	5.1	1.0	1.7	0.30	0.06	0.12
I24	Manufacture of Non-metallic Mineral Products	4.97	0.75	2.61	7.4	3.0	4.4	0.56	0.14	0.22
I25	Smelting and Pressing of Ferrous Metals	6.82	1.45	4.54	17.6	2.9	11.2	1.91	0.57	1.11
I26	Smelting and Pressing of Non-ferrous Metals	4.44	0.50	2.42	4.9	2.7	3.2	1.87	0.27	0.89
I27	Manufacture of Metal Products	3.15	0.53	1.71	3.5	1.1	2.3	0.27	0.04	0.14
I28	Manufacture of General Purpose Machinery	4.07	0.77	2.58	2.4	0.8	1.5	0.12	0.04	0.08
I29	Manufacture of Special Purpose Machinery	3.01	0.52	1.70	2.1	0.6	1.2	0.56	0.06	0.15
I30	Manufacture of Transport Equipment	7.44	1.56	4.22	6.0	1.6	3.8	0.79	0.09	0.30
I31	Manufacture of Electrical Machinery and Equipment	5.80	1.06	3.40	1.3	0.7	1.0	0.08	0.03	0.05
I32	Manufacture of Communication Equipment, Computers and Other Electronic Equipment	7.40	2.25	4.89	3.7	1.2	2.6	0.32	0.08	0.22
I33	Manufacture of Measuring Instruments and Machinery for Cultural Activity and Office Work	0.72	0.23	0.52	1.3	0.1	0.6	0.07	0.01	0.03
I34	Manufacture of Artwork and Other Manufacturing	0.67	0.17	0.34	0.9	0.2	0.5	0.05	0.01	0.03
I35	Recycling and Disposal of Waste	0.32	0.01	0.15	0.3	0.0	0.2	0.02	0.00	0.01
I36	Production and Supply of Electric Power and Heat Power	4.94	1.58	3.47	13.2	2.5	6.5	0.55	0.13	0.29
I37	Production and Supply of Gas	0.45	0.06	0.21	11.8	0.1	1.6	0.63	0.02	0.20
I38	Production and Supply of Water	0.15	0.06	0.10	2.5	0.0	1.2	0.28	0.00	0.10

Note: Max, Min and Mean denoted the maximum value, the minimum value and the average value of the corresponding indicators among the 38 sub-sectors, respectively.

Table A2. Detailed multiplicative decomposition results of COD and NH_3-N changes.

Stage	COD					NH_3-N				
	ΨY_{TOT}	ΨY_G	ΨY_S	ΨY_C	ΨY_A	ΨY_{TOT}	ΨY_G	ΨY_S	ΨY_C	ΨY_A
2003–2004	0.9848	1.4235	0.9957	0.71	0.9785	1.0295	1.4247	0.9936	0.7254	1.0026
2004–2005	1.0737	1.0948	0.9841	1.018	0.979	1.2375	1.0942	1.0222	0.952	1.1622
2005–2006	0.9508	1.2151	0.9829	0.8353	0.9531	0.7592	1.2142	0.9923	0.8181	0.7702
2006–2007	0.9813	1.1839	0.9981	0.955	0.8696	0.8154	1.1837	1.0092	0.8743	0.7807
2007–2008	0.8997	1.1607	0.9961	0.8676	0.897	0.8666	1.1605	1.0021	0.8451	0.8817
2008–2009	0.9403	1.0915	1.0115	0.8773	0.9707	0.914	1.0912	1.0067	0.8878	0.9372
2009–2010	0.9625	1.2058	0.9924	0.852	0.9441	0.9936	1.2053	1.0023	0.8505	0.967
2010–2011	0.8162	1.1157	1.008	2.0433	0.3552	1.1502	1.1179	1.0231	2.3157	0.4343
2011–2012	1.0398	1.0776	1.002	0.903	1.0665	0.9234	1.0789	1.0102	0.8685	0.9755
2012–2013	0.9385	1.0891	0.9972	1.3047	0.6623	0.9276	1.0891	1.0044	1.4697	0.577
2013–2014	0.9634	1.0409	0.978	0.6323	1.4968	0.9368	1.0406	0.9909	0.5066	1.7935
2003–2005	1.0573	1.5569	0.9836	0.7215	0.957	1.274	1.5585	1.018	0.6826	1.1764
2005–2010	0.7598	2.1866	0.9811	0.5171	0.6849	0.4872	2.1651	1.0173	0.4657	0.4749
2010–2014	0.7673	1.3627	0.9889	1.4844	0.3836	0.9229	1.3637	1.022	1.4897	0.4445
2003–2014	0.6164	4.4543	0.9742	0.5464	0.26	0.5728	4.4404	1.0698	0.4729	0.255

Table A3. Detailed additive decomposition results of COD and NH_3-N changes (unit: Mt).

Stage	COD					NH_3-N				
	$\triangle Y_{TOT}$	$\triangle Y_G$	$\triangle Y_S$	$\triangle Y_C$	$\triangle Y_A$	$\triangle Y_{TOT}$	$\triangle Y_G$	$\triangle Y_S$	$\triangle Y_C$	$\triangle Y_A$
2003–2004	−0.067	1.551	−0.019	−1.505	−0.095	0.011	0.132	−0.002	−0.119	0.001
2004–2005	0.321	0.409	−0.073	0.081	−0.096	0.090	0.038	0.009	−0.021	0.063
2005–2006	−0.230	0.889	−0.079	−0.822	−0.219	−0.112	0.079	−0.003	−0.082	−0.107
2006–2007	−0.083	0.744	−0.008	−0.203	−0.616	−0.065	0.054	0.003	−0.043	−0.079
2007–2008	−0.438	0.618	−0.016	−0.589	−0.450	−0.039	0.040	0.001	−0.045	−0.034
2008–2009	−0.235	0.334	0.044	−0.499	−0.113	−0.022	0.021	0.002	−0.029	−0.016
2009–2010	−0.138	0.678	−0.028	−0.581	−0.208	−0.001	0.043	0.001	−0.037	−0.008
2010–2011	−0.654	0.352	0.026	2.300	−3.332	0.034	0.027	0.006	0.205	−0.204
2011–2012	0.116	0.221	0.006	−0.302	0.191	−0.020	0.019	0.003	−0.035	−0.006
2012–2013	−0.186	0.250	−0.008	0.778	−1.205	−0.017	0.020	0.001	0.090	−0.128
2013–2014	−0.104	0.111	−0.062	−1.275	1.121	−0.014	0.009	−0.002	−0.148	0.127
2003–2005	0.254	2.016	−0.075	−1.486	−0.200	0.100	0.184	0.007	−0.158	0.067
2005−2010	−1.125	3.203	−0.078	−2.699	−1.550	−0.239	0.257	0.006	−0.254	−0.248
2010–2014	−0.828	0.967	−0.035	1.234	−2.994	−0.018	0.068	0.005	0.087	−0.177
2003–2014	−1.698	5.244	−0.092	−2.121	−4.729	−0.157	0.419	0.019	−0.210	−0.384
Average	−0.154	0.477	−0.008	−0.193	−0.430	−0.014	0.038	0.002	−0.019	−0.035

Table A4. Cumulative decomposition results converted from the multiplicative results (2003 = 1).

Year	COD					NH_3-N				
	ΨY_{TOT}	ΨY_G	ΨY_S	ΨY_C	ΨY_A	ΨY_{TOT}	ΨY_G	ΨY_S	ΨY_C	ΨY_A
2004	0.9848	1.4235	0.9957	0.7100	0.9785	1.0295	1.4247	0.9936	0.7254	1.0026
2005	1.0574	1.5584	0.9799	0.7228	0.9580	1.2740	1.5589	1.0157	0.6906	1.1652
2006	1.0054	1.8937	0.9631	0.6037	0.9130	0.9672	1.8928	1.0078	0.5650	0.8975
2007	0.9866	2.2419	0.9613	0.5766	0.7940	0.7887	2.2405	1.0171	0.4939	0.7006
2008	0.8876	2.6022	0.9575	0.5002	0.7122	0.6835	2.6001	1.0192	0.4174	0.6178
2009	0.8346	2.8403	0.9685	0.4389	0.6913	0.6247	2.8373	1.0261	0.3706	0.5790
2010	0.8033	3.4248	0.9612	0.3739	0.6527	0.6207	3.4198	1.0284	0.3152	0.5599
2011	0.6557	3.8211	0.9689	0.7640	0.2318	0.7139	3.8230	1.0522	0.7299	0.2431
2012	0.6818	4.1176	0.9708	0.6899	0.2472	0.6592	4.1246	1.0629	0.6339	0.2372
2013	0.6398	4.4845	0.9681	0.9001	0.1638	0.6115	4.4921	1.0676	0.9317	0.1369
2014	0.6164	4.6679	0.9468	0.5691	0.2451	0.5729	4.6745	1.0579	0.4720	0.2455

Note: "2003 = 1" indicated the corresponding values in 2003 were supposed as 1, and the values in the other years were the relative values divided by the values of 2003.

References

1. Tsuzuki, Y.; Koottatep, T.; Sinsupan, T.; Jiawkok, S.; Wongburana, C.; Wattanachira, S.; Sarathai, Y. A concept for planning and management of on-site and centralised municipal wastewater treatment systems, a case study in Bangkok, Thailand. I: Pollutant discharge indicators and pollutant removal efficiency functions. *Water Sci. Technol.* **2013**, *67*, 1923–1933. [CrossRef] [PubMed]
2. Mailler, R.; Gasperi, J.; Coquet, Y.; Bulete, A.; Vulliet, E.; Deshayes, S.; Zedek, S.; Mirande-Bret, C.; Eudes, V.; Bressy, A.; et al. Removal of a wide range of emerging pollutants from wastewater treatment plant discharges by micro-grain activated carbon in fluidized bed as tertiary treatment at large pilot scale. *Sci. Total Environ.* **2016**, *542*, 983–996. [CrossRef] [PubMed]
3. Hou, L.L.; Xia, J.; Li, K.Y.; Chen, J.; Wu, X.L.; Li, X.Q. Removal of ZnO nanoparticles in simulated wastewater treatment processes and its effects on COD and NH_4^+-N reduction. *Water Sci. Technol.* **2013**, *67*, 254–260. [CrossRef] [PubMed]
4. Raja, M.M.M.; Raja, A.; Imran, M.M.; Gajalakshmi, P.; Vignesh, S.; Sivakumar, J. Application of synergetic microorganisms to remove ammonia-nitrogen and chemical oxygen demand from the effluent. *J. Pure Appl. Microbiol.* **2010**, *4*, 659–666.
5. Healy, M.G.; Rodgers, M.; Mulqueen, J. Performance of a stratified sand filter in removal of chemical oxygen demand, total suspended solids and ammonia nitrogen from high-strength wastewaters. *J. Environ. Manag.* **2007**, *83*, 409–415. [CrossRef] [PubMed]
6. Pirsaheb, M.; Azizi, E.; Almasi, A.; Soltanian, M.; Khosravi, T.; Ghayebzadeh, M.; Sharafi, K. Evaluating the efficiency of electrochemical process in removing COD and NH_4-N from landfill leachate. *Desalin. Water Treat.* **2016**, *57*, 6644–6651. [CrossRef]
7. Huang, Y.K.; Li, S.; Wang, C.; Min, J. Simultaneous removal of COD and NH_3-N in secondary effluent of high-salinity industrial waste-water by electrochemical oxidation. *J. Chem. Technol. Biotechnol.* **2012**, *87*, 130–136. [CrossRef]
8. Candido, L.; Gomes, J.; Jambo, H.C.M. Electrochemical treatment of oil refinery wastewater for NH_3-N and COD removal. *Int. J. Electrochem. Sci.* **2013**, *8*, 9187–9200.
9. Huang, W.L.; Wang, W.L.; Shi, W.S.; Lei, Z.F.; Zhang, Z.Y.; Chen, R.Z.; Zhou, B.B. Use low direct current electric field to augment nitrification and structural stability of aerobic granular sludge when treating low COD/NH_4-N wastewater. *Bioresour. Technol.* **2014**, *171*, 139–144. [CrossRef] [PubMed]
10. Ramdani, N.; Lousdad, A.; Tilmatine, A.; Nemmich, S. Dielectric barrier discharge-based investigation and analysis of wastewater treatment and pollutant removal. *Water Sci. Technol.* **2016**, *73*, 2858–2867. [CrossRef] [PubMed]
11. Abu Hasan, H.; Abdullah, S.R.S.; Kamarudin, S.K.; Kofli, N.T. Response surface methodology for optimization of simultaneous COD, NH_4^+-N and Mn_2^+ removal from drinking water by biological aerated filter. *Desalination* **2011**, *275*, 50–61. [CrossRef]
12. Kamaruddin, M.A.; Yusoff, M.S.; Ahmad, M.A. Optimization of preparation conditions for durian peel-based activated carbon for the removal of COD and Ammoniacal Nitrogen (NH_3-N) using response-surface methodology. *Kuwait J. Sci. Eng.* **2012**, *39*, 37–58.
13. Muhamad, M.H.; Abdullah, S.R.S.; Mohamad, A.; Rahman, R.A.; Kadhum, A.A.H. Application of response surface methodology (RSM) for optimisation of COD, NH3-N and 2,4-DCP removal from recycled paper wastewater in a pilot-scale granular activated carbon sequencing batch biofilm reactor (GAC-SBBR). *J. Environ. Manag.* **2013**, *121*, 179–190. [CrossRef] [PubMed]
14. Rubi, H.; Fall, C.; Ortega, R.E. Pollutant removal from oily wastewater discharged from car washes through sedimentation-coagulation. *Water Sci. Technol.* **2009**, *59*, 2359–2369. [CrossRef] [PubMed]
15. Zou, J.L.; Xu, G.R.; Pan, K.; Zhou, W.; Dai, Y.; Wang, X.; Zhang, D.; Hu, Y.C.; Ma, M. Nitrogen removal and biofilm structure affected by COD/NH_4^+-N in a biofilter with porous sludge-ceramsite. *Sep. Purif. Technol.* **2012**, *94*, 9–15. [CrossRef]
16. Xie, Y.K.; Wen, Z.Y.; Mo, Z.H.; Yu, Z.Q.; Wei, K.L. Implementation of an automatic and miniature on-line multi-parameter water quality monitoring system and experimental determination of chemical oxygen demand and ammonia-nitrogen. *Water Sci. Technol.* **2016**, *73*, 697–706. [CrossRef] [PubMed]

17. Xinhua News Agency. National Economic and Social Development Report of the People's Republic of China 13th Five-Year-Plan Outline. Available online: http://news.xinhuanet.com/politics/2016lh/2016-03/17/c1118366322.htm (accessed on 20 May 2016).
18. Grossman, G.M.; Krueger, A.B. *Environmental Impacts of a North American Free Trade Agreement*; Working paper No. 3914; National Bureau of Economic Research: Cambridge, MA, USA, 1991.
19. Chowdhury, R.R.; Moran, E.F. Turning the curve: A critical review of Kuznets approaches. *Appl. Geogr.* **2012**, *32*, 3–11. [CrossRef]
20. Haans, R.F.J.; Pieters, C.; He, Z.L. Thinking about U: Theorizing and testing U- and inverted U-shaped relationships in strategy research. *Strat. Mgmt. J.* **2016**, *37*, 1177–1195. [CrossRef]
21. Li, T.; Han, Y.; Li, Y.; Lu, Z.; Zhao, P. Urgency, development stage and coordination degree analysis to support differentiation management of water pollution emission control and economic development in the eastern coastal area of China. *Ecol. Indic.* **2016**, *71*, 406–415. [CrossRef]
22. Pandit, M.; Paudel, K.P. Water pollution and income relationships: A seemingly unrelated partially linear analysis. *Water Resour. Res.* **2016**, *52*, 7668–7689. [CrossRef]
23. Lei, H.; Xia, X.; Li, C.; Xi, B. Decomposition analysis of wastewater pollutant discharges in industrial sectors of China (2001–2009) using the LMDI I method. *Int. J. Env. Res. Public Health.* **2012**, *9*, 2226–2240. [CrossRef] [PubMed]
24. Liu, L.; Wang, S.S.; Wang, K.; Zhang, R.Q.; Tang, X.Y. LMDI decomposition analysis of industry carbon emissions in Henan province, China: Comparison between different 5-year plans. *Nat. Hazards* **2016**, *80*, 997–1014. [CrossRef]
25. Xiao, B.; Niu, D.; Guo, X. The driving forces of changes in CO_2 emissions in China: A structural decomposition analysis. *Energies* **2016**, *9*, 259. [CrossRef]
26. Cansino, J.M.; Roman, R.; Ordonez, M. Main drivers of changes in CO_2 emissions in the Spanish economy: A structural decomposition analysis. *Energ. Policy* **2016**, *89*, 150–159. [CrossRef]
27. Cellura, M.; Longo, S.; Mistretta, M. Application of the structural decomposition analysis to assess the indirect energy consumption and air emission changes related to Italian households consumption. *Renew. Sust. Energ. Rev.* **2012**, *16*, 1135–1145. [CrossRef]
28. Yang, Z.; Liu, H.; Xu, X.; Yang, T. Applying the water footprint and dynamic structural decomposition analysis on the growing water use in China during 1997–2007. *Ecol. Indic.* **2016**, *60*, 634–643. [CrossRef]
29. Hoekstra, R.; van der Bergh, J. Comparing structural and index decomposition analysis. *Energy Econ.* **2003**, *25*, 39–64. [CrossRef]
30. Lu, Z.; Yang, Y.; Wang, J. Factor decomposition of carbon productivity change in China's main industries: Based on the Laspeyre's decomposition method. *Energ. Procedia* **2014**, *61*, 1893–1896.
31. Hatzigeorgiou, E.; Polatidis, H.; Haralambopoulos, D. CO_2 emissions in Greece for 1990–2002: A decomposition analysis and comparison of results using the Arithmetic Mean Divisia Index and Logarithmic Mean Divisia Index techniques. *Energy* **2008**, *33*, 492–499. [CrossRef]
32. Ang, B.W. The LMDI approach to decomposition analysis: A practical guide. *Energ. Policy* **2005**, *33*, 867–871. [CrossRef]
33. Wang, C.; Chen, J.N.; Zou, J. Decomposition of energy-related CO_2 emission in China: 1957–2000. *Energy* **2005**, *30*, 73–83. [CrossRef]
34. Lee, K.; Oh, W. Analysis of CO_2 emissions in APEC countries: A time-series and a cross-sectional decomposition using the Log Mean Divisia method. *Energ. Policy* **2006**, *34*, 2779–2787. [CrossRef]
35. Wood, R.; Lenzen, M. Zero-value problems of the Logarithmic Mean Divisia Index decomposition method. *Energ. Policy* **2006**, *34*, 1326–1331. [CrossRef]
36. Shao, S.; Yang, L.L.; Gan, C.H.; Cao, J.H.; Geng, Y.; Guan, D.B. Using an extended LMDI model to explore techno-economic drivers of energy-related industrial CO_2 emission changes: A case study for Shanghai (China). *Renew. Sust. Energ. Rev.* **2016**, *55*, 516–536. [CrossRef]
37. Chen, S. The abatement of carbon dioxide intensity in China: Factors decomposition and policy implications. *World Econ.* **2011**, *34*, 1148–1167. [CrossRef]
38. Tan, Z.; Li, L.; Wang, J.; Wang, J. Examining the driving forces for improving China's CO_2 emission intensity using the decomposing method. *Appl. Energ.* **2011**, *88*, 4496–4504. [CrossRef]
39. Ren, S.; Fu, X.; Chen, X. Regional variation of energy-related industrial CO_2 emissions mitigation in China. *China Econ. Rev.* **2012**, *23*, 1134–1145. [CrossRef]

40. Zhang, M.; Liu, X.; Wang, W.; Zhou, M. Decomposition analysis of CO_2 emissions from electricity generation in China. *Energ. Policy* **2013**, *52*, 159–165. [CrossRef]
41. Tian, Y.; Zhu, Q.; Geng, Y. An analysis of energy-related greenhouse gas emissions in the Chinese iron and steel industry. *Energ. Policy* **2013**, *56*, 352–361. [CrossRef]
42. Ang, B.W.; Liu, F.L. A new energy decomposition method: Perfect in decomposition and consistent in aggregation. *Energy* **2001**, *26*, 537–548. [CrossRef]
43. Ang, B.W.; Liu, F.L.; Chew, E.P. Perfect decomposition techniques in energy and environmental analysis. *Energ. Policy* **2003**, *31*, 1561–1566. [CrossRef]
44. Ang, B.W. Decomposition analysis for policymaking in energy: Which is the preferred method? *Energ. Policy* **2004**, *32*, 1131–1139. [CrossRef]
45. Ang, B.W.; Liu, N. Handling zero values in the Logarithmic Mean Divisia Index decomposition approach. *Energ. Policy* **2007**, *35*, 238–246. [CrossRef]
46. Ang, B.W. Decomposition Methodology in Energy Demand and Environmental Analysis. In *Handbook of Environmental and Resource Economics*; van den Bergh, J.C.J.M., Ed.; Edward Elgar Publishers: Cheltenham, UK, 1999.
47. Ma, C.B.; Stern, D.I. China's changing energy intensity trend: A decomposition analysis. *Energ. Econ.* **2008**, *30*, 1037–1053. [CrossRef]
48. Sun, J.W. Changes in energy consumption and energy intensity: A complete decomposition model. *Energ. Econ.* **1998**, *20*, 85–100. [CrossRef]
49. Zhang, K.M.; Wen, Z.G. Review and challenges of policies of environmental protection and sustainable development in China. *J. Environ. Manag.* **2008**, *88*, 1249–1261. [CrossRef] [PubMed]