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How Does Technological Innovation Mediate the Relationship between Environmental Regulation and High-Quality Economic Development? Empirical Evidence from China

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Abstract: Technological innovation is considered to be an effective way to promote the quality of economic development and green transition under environmental policies, while the specific mechanism of this process is still unclear. Thus, the purpose of this paper was to examine how technological innovation mediates the relation between environmental regulation and high-quality economic development. Based on the panel data of 34 industries in China from 2007 to 2015, this paper firstly calculated the green total factor productivity (GTFP) as a proxy variable for the quality of economic development through the super-slack-based measure model, and then analyzed the impact of environmental regulation and technical innovation on the GTFP by making use of the mediation effect model. The results showed that environmental-related policy directly affected the GTFP while technological innovation indirectly moderated this process, where the moderate impact of technological innovation was industrial heterogeneous. Specifically, the relation between environmental regulation and GTFP was positively and partially moderated by technological innovation in clean industries and high-tech industries, while positively but completely moderated by technological innovation in low-and medium-tech industries. Moreover, the mediating effect of technological innovation in pollution-intensive industries was positive but insignificant.

Keywords: environmental policy; technological innovation; GTFP; mediation effect

1. Introduction

After years of efforts, China's economy has shifted from a stage of rapid growth to a stage of high-quality development, and it is presently in a critical period of transformational development where it is optimizing economic structure and transforming growth momentum. However, the ecological and environmental problems accumulated in the past 30-plus years have become increasingly serious. As China enters the window period to solve the prominent problems of ecological environment and the critical period when the economy turns to high-quality development, it is of practical importance to examine alternatives to address ecological civilization construction and economic quality upgrading, and consequently to realize the coordination of environment sustainability and quality-based economic growth. Enhancing the construction of ecological civilization and promoting green development are central to achieving high-quality development. Ecological civilization has been written into China's constitution as the ideological framework for the country's environmental policies [1]. Can environmental regulation boost the development of economic quality? Theory and experience show that technological innovation is the key driving force for achieving long-term green economic development under the constraints of environmental policies. What role does technological innovation play in the relationship between environmental regulation and high-quality economic development?

The essential characteristic of high quality development is to meet people's needs in a variety of effective and sustainable ways [2], while promoting total factor productivity

(TFP) is the key to achieving high-quality development [3]. In addition, most prior studies use a single indicator such as TFP [4], labor productivity [5], gross domestic product (GDP) [6], etc. to measure the quality of economic growth. In the face of environmental deterioration, how industries respond to or comply with environmental regulation through innovation as for leading to economic growth and environmental optimization needs to be addressed. Green total factor productivity (GTFP) takes into account both the increase of expected output and the decrease of unexpected output, which is consistent with the concept of green development that needs to be realized in the process of high-quality economic development. In this respect, the GTFP index is expected to reflect these features of high-quality development, which is applied to measure the economic development quality, focusing on the dual effect of regulatory policy and technical innovation on GTFP.

Previous studies have extended this topic in different fields such as environmental regulation and pollution control [7], environmental regulation and technological innovation [8,9], cross domain governance and pollution reduction [10,11], and the relationship between technological innovation and economic growth [12,13]. Although much of the literature has paid attention to the interaction of environmental policy and technical innovation, or the interaction of environmental policy and GTFP, few studies intend to bring environmental policy, technical innovation, and GTFP into the same analytic framework. The empirical approach of this field is still limited to the two-way relationship as well. Thus, this paper attempts to make a systematic analysis from the perspectives of technological innovation, environmental regulation, and GTFP.

Theoretically, the strong version of the Porter hypothesis suggests that well-designed environmental regulation is supposed to trigger technological innovation and consequently promote green growth [14,15]. The key mechanism in this respect is that elaborated regulation is likely to internalize enterprises' compliance cost by encouraging corporate innovation activities, developing green technology. or introducing clean technology [13]. Then, the innovation compensation effect can moderate this process by improving production efficiency and offsetting the compliance cost increased by environmental regulation, which can ultimately improve environmental quality and even the green total factor productivity. Moreover, the main contribution of the 2018 Nobel Prize winners Paul M. Romer and William D. Nordhaus was to integrate the factors of climate change and technological innovation into a macroeconomic analysis. They believed that technological innovation was the most important solution to coordinate the relationship between environmental governance, climate change, and economic development. However, the specific role of environmental regulation on improving GTFP is still confusing [12,16], and there is a lack of empirical results in China.

Although these researches have made a useful attempt to theoretically study innovation's impact on GTFP, the specific role of technological innovation in heterogeneous industrial and regional pollution governance process has yet to be analyzed in China. Different institutional background and technological basis lead to different innovation behaviors in heterogeneous industries [17,18]. Strict environmental regulation can drive green behavior of high-tech industries in developed regions that have a rationalized institutional structure and arrangement [19], which effectively weaken the market failure caused by the externalities of green innovation. Thus, it is of great value to examine the relationship between environmental regulation and green technology innovation from the perspective of heterogeneous effects on industrial innovation behaviors.

This research analyzed the role of technological innovation in shaping the relationship between the mechanism of environmental regulation and GTFP. In addition, there were dramatic industrial differences of pollution discharge and technology basis. Thus, industrial heterogeneity was found to be necessary in the context of China. This involved two innovative works. First, a technical change was used as a mediator to analyze the conducive effect that environmental policy had on GTFP, which extended the literature on research of the relations between environment-related policies and the GTFP. Second, using China's industrial data from 2007 to 2015 for quantitative analysis, the intermediary effect

of technological innovation was empirically tested on the divided industries according to different pollution levels and technological levels. The purpose of this study was to identify the role of technological innovation in the relationship between environmental regulation and GTFP in different industries, verify the transmission path of environmental policy on the GTFP, and provide reference for the government to develop sound environmental policies and innovation policies.

This paper is organized as follows: Section 2 provides an overview of the related literature and proposes the research hypotheses; Section 3 presents the measurement and decomposition of green total factor productivity; Section 4 introduces the design and methodology of this study and shows the variables chosen as well as data sources; Section 5 describes our empirical results and presents our discussion. Finally, Section 6 provides conclusions and policy implications.

2. Literature Review and Research Hypothesis

2.1. The Relationship between Environmental Regulation and Technological Innovation

The Porter's hypothesis firstly proposed by Porter and van der Linder [14] points out that strict and appropriate environmental policies stimulate innovative activities for enterprises, which partially or even fully can offset enterprises' compliance cost under environment-related regulations, which could consequently improve their international competitiveness. However, Porter's hypothesis does not provide a clear analytic framework for empirical studies. Present studies divide Porter hypothesis into three levels: narrow version, the weak form, and the strong form [15]. Empirical studies of this domain mainly focus on how environment-related governance induce the overall innovation activities (the weak form of Porter-hypothesis) and total factor productivity (the strong form of Porter-hypothesis). The former holds that elaborated and well-designed environmental policies may induce innovation, while it is still unclear if enterprises will benefit from these innovative activities. In pursuit of profit maximization, environmental standards impose additional constraints on enterprises. Thus, enterprises are likely to alter their normal production activities to their innovative counterparts to cut down costs under the new constraints. Empirically, Jaffe and Palmer [15] suggest that environmental policy has an essential role in promoting private research and development (R&D) investment, while having no significant impact on patent applications. Some scholars, however, have only found a positive relation between regulatory policy and the environmental-related patent application [20,21]. Moreover, using China's data, Shen et al. [22] and Jiang et al. [23] presented a U-shaped relation between environment-related policy and technical innovation. Therefore, the present literature has not yet reached consensus on how environmental policy impacts technical innovation in terms of innovation input (R&D investment or patent) and innovation output.

Two impact mechanisms of environmental policy on technical innovation are analyzed and discussed to explain this confusion: the positive compensation effect and negative offset effect. On the one hand, technological innovation is supposed to occupy and use up a lot of capital of enterprises while pollution abatement cost is increased by environmental regulations. Thus, production activities rather than innovation activities are favored regarding the limited resources of enterprises, which consequently crows out the R&D investment. Meanwhile, stricter regulations lead to significant private investments in fields of relatively lower regulatory intensity. On the other hand, pollution abatement cost is likely to be increased by environmental management, introducing or developing new green/clean technology. As for profit maximization, innovative activities can reduce costs for enterprises under new constraints. Specifically, production efficiency and pollution control capacity can be improved through technological innovation, which consequently slows down or reduces the pollution abatement costs of enterprises. Therefore, the existence of the Porter hypothesis depends on the combined effect between offset and compensation.

Traditional cost view holds that environmental policy is not conducive to innovative activities of enterprises, while the incentive counterpart holds that environmental regula-

tion will stimulate it. This controversial view suggests that regulation has both offset and compensation effects on technological renovation, and the result depends on the scale and direction of each. Accordingly, research Hypothesis 1 is put forward.

Hypothesis 1 (H1). *Regulatory policy promotes technical innovation of enterprises and thereby verifies the weak Porter hypothesis.*

2.2. The Relationship between Environmental Regulation and GTFP

A well-structured environmental policy is recognized to have positive impact on industrial GTFP [24–26]. Specifically, a U-shaped effect between regulations intensity and GTFP of manufacturing industries has been empirically tested [27,28]. On the contrary, Cai and Zhou [29] found a direct inverted U-shaped relation between the market-motivated environmental policy and GTFP, while this relationship was indirectly affected by the heterogeneity of regional technical innovation, factor structure, and foreign investment level (FDI) level. Moreover, there is a distinct threshold effect for regulations to promote GTFP, i.e., the influence of regulations on GTFP can change from positive to negative when the environmental regulation intensity (ERI) meets or exceeds a threshold that the compliance costs are much higher than innovative offset effects [30]. This threshold effect changes with the ERI, the level of scientific and technological innovation, and the ownership structure [31]. Besides the threshold effect, regional differences [32], policy heterogeneity [33], and time effects [34] of regulations on GTFP have recently received wide concern. Thus, the impact mechanism of ERI on GTFP should be further explained to clarify the directly and indirectly influential process, as well as the role of industrial characteristics.

As for the strict regulations, enterprises have to reduce pollution emissions through changing production factors originally used for production to other unproductive activities. Although this process hopes to trigger enterprises' creation and adoption of green/clean technology, the additional loss of environmental protection equipment and the reduction of the matching production material with the original production equipment eventually results in productivity losses. On the other hand, environmental regulation crows out those enterprises with low productivity and serious pollution, and leaves clean and high-productivity enterprises to consequently contribute to the overall productivity or competitiveness.

The innovation compensation view of the "strong" version holds that innovation induced by regulations will offset the environmental cost of enterprises and ultimately improve the overall performance. Empirical evidence shows that environmental protection regulation can significantly improve GTFP, while it is not proved that the improvement of GTFP is caused by regulation-induced innovation. Owing to the diversified industrial development level and environmental characteristic, this paper holds that there is obvious industrial discrepancy in the impact of environment policy on the GTFP. For this respect, research Hypothesis 2 is put forward.

Hypothesis 2 (H2). *Environmental regulation positively influences green total factor productivity, and with significant industrial heterogeneity.*

2.3. Mediation Role of Technological Innovation

Some scholars have found that environmental policy will crow out private R&D expenditure, and results in a negative effect on patent output and the GTFP [12]. While green innovation is supposed to moderate this process, regulation-induced innovation can improve green productivity [35]. Innovation based on invention patents is considered to be the driving factor for promoting the green growth of industries [36]. Specifically, market-motivated environmental policy is likely to stimulate green process innovation and hence positively affect green performance, while green product innovation is expected to promote sustainable development in the absence of regulatory policy [37]. Therefore, a well-

structured environmental regulation is likely to stimulate enterprises' technical innovation motivation [38], improve commercial competitiveness and productive performance [39,40], and consequently enhance resource utilization efficiency. The improvement of enterprise's technical innovation capacity hopes to make enterprises more quickly adapt to specific environmental regulation and achieve rapid development.

Theoretically, the "weak" Porter hypothesis holds that environmental policy promotes firms to carry out innovative activities, which effectively enhance the existing technical level of the enterprises. With previous technology substituted by new productive technology, the frontier of the production possibility is extended as expected. At the new technical level, the same amount of output needs less input and even less emissions, which consequently profits more. The induced technical innovation activities by regulations make enterprises arrive at a new frontier of the production possibility, which is likely to maximize profits and increase productivity [41]. Under the assumption of industrial heterogeneity, environmental regulation may lead to different behavioral decisions of enterprises in the industries in terms of market withdrawal and technology innovation, which have a heterogeneous impact on green performance. Due to the difference of technological distance between different industries based on the frontier, different behavioral decisions can be made under regulation pressure, which mean that not all enterprises can achieve GTFP growth through innovation activities.

With respect to the indirect effects, regulatory policy has an uncertain impact on green performance through technical innovation. According to the cost theory based on neoclassical economics, environmental supervision leads to the rising cost of pollution control, offsets productive investment and innovation activities, restricts technological renovation, and indirectly has a negative effect on green overall productivity [42]. The revisionist school, represented by Porter, holds that the scientifically designed environmental protection regulation promotes enterprises to internalize environmental costs actively. By encouraging enterprises to carry out innovative activities, develop green technology, or introduce clean technology, it improves organizational management, improves input-output efficiency, and offsets the cost increase induced by environmental regulation, which thus produces innovation compensation effect and improves green performance [14]. Previous studies on this issue have mainly focused on the relationship between regulations and GTFP; few studies have brought environmental policy, technical innovation, and GTFP to the same analytic framework. Therefore, this paper contributes to present literature by introducing the technical renovation as an intermediary variable, and empirically tests the casual effects between regulation-induced innovation and GTFP. Specifically, this paper holds that technological innovation plays an intermediary role between regulations and GTFP. According to Porter's hypothesis, appropriate environmental regulation is able to encourage the regulated enterprises or industries to carry out technological innovation, so as to promote industrial upgrading. Under the guidance of environmental governance, technological innovation is expected to realize resource conservation, industry green, and ecological consumption, which consequently benefits the economic growth, ecological environment, and social welfare, being eventually conducive to the green total factor productivity and high-quality economic development [43]. Thus, Hypothesis 3 is put forward.

Hypothesis 3 (H3). *Environmental regulation not only directly affects GTFP but also produces an intermediary effect through technological innovation.*

Based on the literature analyzed above, the framework describing how environmental regulation impacts technological innovation and GTFP is shown in Figure 1.
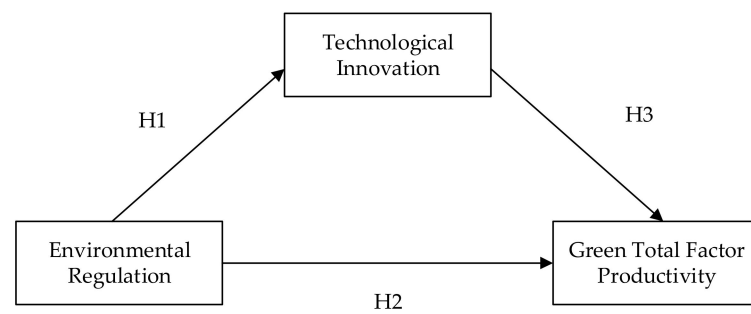
Technological Innovation

H1   H3

Environmental Regulation → Green Total Factor Productivity

H2

Figure 1. Theoretical model.

3. Measurement and Decomposition of Green Total Factor Productivity

3.1. Indicator Setting and Context

GTFP overcomes the deficiency that environmental-related problems—absent in the analysis of traditional TFP—can comprehensively consider, i.e., productivity under the unexpected output. This paper intends to use the super-efficiency SBM model based on undesired outputs to calculate the industrial GTFP. It is necessary to construct the relevant indicators of desired output, undesired output and input.

(1) Desirable outputs. Since the GDP has not been published since 2012, the industrial sales output value, which is close to the GDP, was used to represent undesirable output in this paper, according to Liu [44].

(2) Undesirable outputs. As for undesirable outputs, the previous literature on this indicator varied. The cost of pollution treatment in China only includes the waste gas treatment fee and wastewater treatment fee. Thus, the amount of waste gas discharge and wastewater discharge were used as the unexpected output in this paper.

(3) Input. Capital input was obtained by deducting depreciation over years from the original value of fixed assets; labor force was calculated by the annual average number of employees in all industrial sectors in the "China Industrial Yearbook"; energy input was collected from the energy consumption of the industrial sub-sectors.

3.2. Data Source and Processing

All sample data sources were retrieved from the Chinese Statistical Yearbook, Chinese Industrial Statistics Yearbook, and Chinese Environmental Statistics Yearbook, ranging from 2008 to 2016. With respect to the missing data and inconsistent divisions problems in 2012, this paper also considered the following data.

(1) Industrial division. The classification of national economic industries underwent three adjustments during the sample period (2007–2015). Industries such as ancillary activities for exploitation, mining of other ores, other manufactures, utilization of waste resources, metal products, machinery and equipment repair, and production and distribution of water were deleted for incompleteness. While manufacture of automobile, manufacture of railway, shipbuilding, aerospace, and other transportation equipment were merged into manufacture of transport equipment. Manufacture of rubber and manufacture of plastic were merged into manufacture of rubber and plastic. Thus, 34 industry segments were eventually obtained (the industry list and industry codes are shown in Appendix A).

(2) Missing value processing. Due to the lack of labor data in the industrial sub-sectors in 2012, this paper calculated the monthly employees of the sub-industries published in the Wind database.

3.3. Results and Analysis of GTFP

According to 34 industrial input-output data from 2007 to 2015, this paper used the GML index (Global Malmquist Luenberger index: A calculation method of Malmquist index based on DDF distance) and MAXDEA ULTRA software to calculate the green total

factor productivity index. The ML index (Malmquist Luenberger index: A Malmquist index calculation method considering undesired output) reflects the growth rate of GTFP, namely, relative to last year's variation in GTFP. For this respect, this paper referred to Chen [45], assuming that the GTFP in 2007 was 1, and then multiplied the calculated ML index to obtain the GTFP of different industries from 2008 to 2015. The measurement of ML decomposition term was consistent with the ML index. As such, the adjusted ML index and its decomposition for 2007-2015 could be finally obtained, where the specific calculation results of GTFP and its decomposition in China's sub-sectors are reported in Table 1.

Table 1. Green total factor productivity (GTFP) and its decomposition in China's industrial segmentation industry (2007–2015).

Industries	GEFFCH	GTECH	GTFP
(1)	1.478	0.840	1.213
(2)	0.845	1.317	1.096
(3)	1.298	0.962	1.251
(4)	1.207	0.835	0.995
(5)	0.957	0.990	0.943
(6)	0.965	0.996	0.960
(7)	1.143	0.987	0.960
(8)	1.075	0.890	0.956
(9)	0.977	1.259	1.239
(10)	1.150	0.816	0.936
(11)	0.847	1.160	0.971
(12)	0.843	0.897	0.764
(13)	1.052	1.162	1.217
(14)	0.883	1.164	1.022
(15)	0.940	0.651	0.609
(16)	0.960	1.301	1.245
(17)	0.987	1.323	1.299
(18)	1.009	1.578	1.592
(19)	0.921	0.934	0.861
(20)	1.025	1.007	1.031
(21)	0.938	0.853	0.796
(22)	0.694	1.322	0.880
(23)	0.746	1.175	0.868
(24)	0.939	0.827	0.777
(25)	0.841	1.151	0.966
(26)	0.994	1.038	1.026
(27)	1.006	1.151	1.150
(28)	0.972	1.169	1.113
(29)	1.058	1.130	1.199
(30)	0.714	1.469	1.022
(31)	0.754	1.334	0.976
(32)	0.650	1.232	0.783
(33)	0.990	1.426	1.416
(34)	1.192	1.213	1.448
Average Value	0.972	1.105	1.046

In Table 1, the average GTFP is shown to be 1.046, of which the green technology efficiency was 0.972 and the green technology progress was 1.105. In terms of the overall change range of GTFP, the average growth rate of GTFP was 4.6%. Among them, the efficiency of green technology decreased by 2.8%, and the progress of green technology increased by 10.5%. Therefore, the growth of GTFP mainly came from the progress of green technology. This suggests that, under the constraints of regulative policy, technological innovation and progress could effectively promote the green industrial transformation. According to the results of specific industries, the main contribution of GTFP came from the efficiency of green technology, which can be seen in resource-based industries such as

mining and washing coal, mining and processing ferrous metal ores, mining and processing non-ferrous metal ores, production and supply of gas, and light textile industries such as manufacture of foods, manufacture of wine, drinks, and refined tea, and manufacture of textile.

In high-tech industries such as manufacture of general purpose machinery, manufacture of special purpose machinery, manufacture of transport equipment, manufacture of electrical machinery and equipment, and manufacture of measuring instrument, the main contribution of GTFP came from the progress of green technology.

With the comparison of the Malmquist productivity index and its decomposition of Chinese industrial subdivisions from 2007 to 2015, the average annual growth rate of GTFP was 1.3%, the average annual growth rate of green technology efficiency was −0.1%, and the average annual growth rate of green technology progress was 1.9%. This shows that the inefficiency of green creation still exists in Chinese industries, and the overall efficiency of green technology needs to be further improved. The dominant driving force of the current industrial GTFP growth lies in the progress of green technology [46].

Figure 2 shows the growth tendency of industrial GTFP and its decomposition in 2007–2015. Generally, the variation of GTFP rate, green technology efficiency, and green technology progress in China's industry fluctuate upward and downward. The change range was large before 2013, and gradually converged after 2013. This suggests that China's economy has changed from a fast speed, huge energy consumption, and high pollution mode to the green development mode characterized with the "new normal" of medium and low speed growth, low energy consumption, and low emissions.
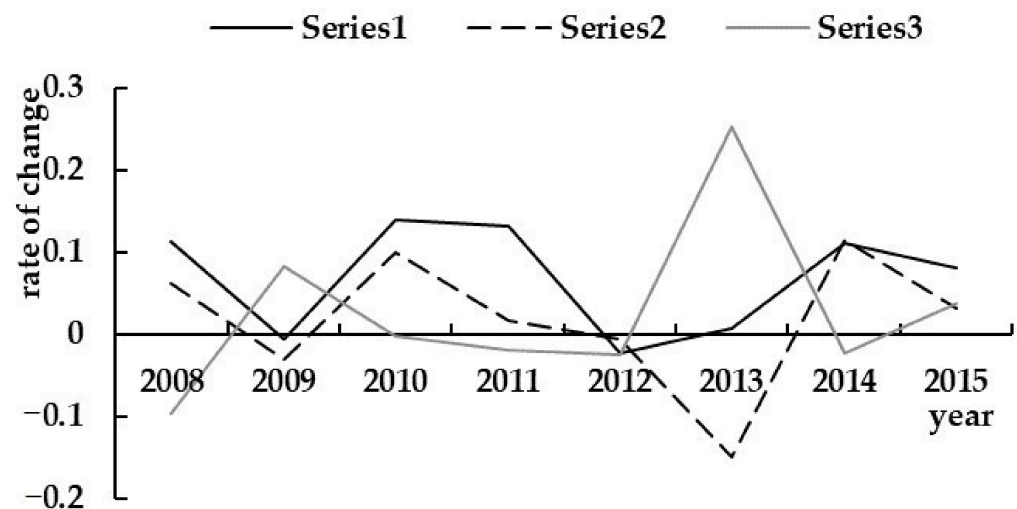

Figure 2. Growth trends of industrial GTFP and its decomposition in China, 2007–2015.

4. Modelling Strategy

4.1. Model Specification

In order to further study the direct impact of environmental regulation on GTFP and the indirect impact of environmental regulation on GTFP through technological innovation, the mediation effect model was used in this paper [47]. This suggests that if the influence of explanatory variable X on interpreted variable Y was decomposed, it included not only the direct effect of X on Y but also the indirect effect of intermediate variable M on Y. Then, M would be the mediation variable, i.e., the mediation variable was the internal conduction medium of the indirect effect of explanatory variable on interpreted variable Y. The conduction mechanism reflected by the mediation effect was exactly consistent with the theoretical hypothesis 3 above, so this paper tested hypothesis 3 by measuring the mediation effect. The test procedure for the mediation effect was to first construct the regression Equation (1) of the explanatory variable X to the explained variable Y, and test whether the coefficient of X was significant. If it was not significant then there was no

stable relationship between X and Y, and the mediation effect would not be discussed; if the regression coefficient was significant, the second step of testing was to construct the regression Equation (2) of the explanatory variable X versus the mediating variable M, and the regression Equation (3) of the explanatory variable X and the mediating variable M versus the explained variable Y to test whether the mediation effect existed. If the coefficients of X in Equations (2) and (3) were significant, and the coefficient of variable M in Equation (3) was significant, it was a partial mediation effect; if the coefficient X in Equation (2) was significant, the coefficient M in Equation (3) was significant but the coefficient X was not significant, and then it was a complete mediation effect. In the intermediary effect model, X is environmental regulation, M is technological innovation, and Y is GTFP; φ_1 is the total effect of X on Y, $\varphi_1 \times \eta_2$ is the intermediary effect conducted through the intermediate variable M, and η_1 is the direct effect of X on Y. Based on the above analysis, the econometric models are constructed as follow:

$$\ln gtfp_{it} = \phi_0 + \phi_1 \ln regu_{it} + \phi_2 \ln fdi_{it} + \phi_3 \ln scale_{it} + \phi_4 \ln fixed_{it} + \delta_{it} \qquad (1)$$

$$\ln pat_{it} = \varphi_0 + \varphi_1 \ln regu_{it} + \varphi_2 \ln r\&d_{it} + \varphi_3 \ln fdi_{it} + \varphi_4 \ln scale_{it} \\ + \varphi_5 \ln fixed_{it} + \varphi_6 ownship_{it} + \varepsilon_{it} \qquad (2)$$

$$\ln gtfp_{it} = \eta_0 + \eta_1 \ln regu_{it} + \eta_2 \ln pat_{it} + \eta_3 fdi_{it} + \eta_4 \ln scale_{it} + \eta_5 \ln fixed_{it} + \mu_{it} \quad (3)$$

where Equation (1) represents the total effects of environment policy on GTFP, Equation (2) represents the influences of environment policy on technical innovation, and Equation (3) represents the total effects of regulations on GTFP decomposed into the direct effect of environment policy on GTFP and the intermediary effect of institutional transmission through technological innovation. Among them, i denotes industry; t denotes year; $gtfp_{it}$ denotes industry GTFP; $regu_{it}$ represents industry regulations intensity; fdi_{it} is the level of foreign investment; $scale_{it}$ is industry scale; $fixed_{it}$ denotes level of capital deepening; pat_{it} represents level of technological innovation; $r\&d_{it}$ denotes industry R&D expenditure; and $ownship_{it}$ represents the institutional factors influencing innovation activities.

4.2. Variable Description and Data Source

(1) Green total factor productivity (GTFP). Considering the unexpected output, ML productivity index was used as the GTFP index in this paper, which was calculated with super-efficiency SBM method and converted into cumulative index. Thus, the GTFP of all industries over the sample years was obtained. The specific calculation method and data sources are shown in Section 3.

(2) Environmental regulation intensity (regu). According to Qin [48], a comprehensive index of regulations intensity of industry was constructed by using the entropy value method. The ratio of operation cost of industrial waste gas equipment to waste gas discharge and the ratio of operation cost of wastewater treatment facilities to wastewater discharge were used to calculate the environmental regulation intensity of each industry. Among them, the data of exhaust gas emission, operation cost of exhaust gas treatment equipment, wastewater discharge, and operation cost of wastewater treatment facilities in various industrial subdivisions all came from the China Environmental Statistical Yearbook. Figure 3 presents the average tendency of the regulations stringency in the industrial sector from 2007 to 2015.

(3) Technological innovation level (pat). As for the technological innovation, the R&D expenditure or the number of invention patents is mainly used to measure of technical innovation output. The number of patents has recently become the mainstream indicator in the study of technical innovation. In this paper, the number of invention patent applications was used as the proxy variable of technological innovation, and the data were collected from the Chinese Statistical Yearbook. It should be noted that, thanks to the variation of statistical caliber, the sample data before 2010 came from large- and medium-sized firms, and the data after 2011 came from large- and

medium-sized enterprises, which is consistent with the previous large- and medium-sized firms.
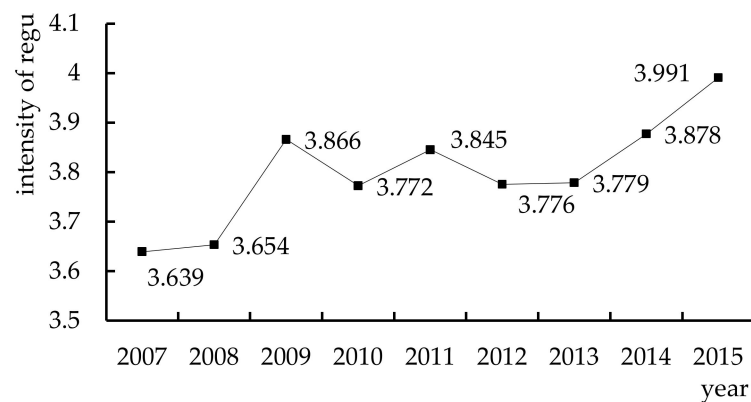

Figure 3. Trends in the average intensity of industrial regulation in China from 2007 to 2015.

(4) Control variables. Control variables. (1) R&D investment represents the input of technical innovation, especially how the intensity of R&D expenditure immediately affects the technical innovation degree of enterprises. The sample data of R&D costs came from the Chinese Statistical Yearbook; (2) foreign investment level (FDI)—the introduction of foreign capital could bring in leading foreign technology and help improve industrial GTFP. The foreign investment in fixed assets of industrial enterprises above scale and those of Hong Kong, Macao, and Taiwan were used to measure the foreign investment degree, and the data came from the Chinese Statistical Yearbook; (3) scale (scale)—the gross industrial output value (RMB 100 million) of enterprises above the industry scale was used as a measurement index in this paper, and the data came from the Chinese Industrial Statistics Yearbook; (4) capital deepening degree (fixed)—fixed assets investments (RMB 100 million) of various industries were used to measure this variable, and the data came from the Chinese Statistical Yearbook; (5) ownership structure was the proportion of the gross domestic product of state-owned and state-owned holding firms to the gross domestic product of industrial enterprises. The data came from the Chinese Statistical Yearbook. In the empirical test, all indicators except ownership structure were in the form of natural logarithm.

4.3. Statistics Descriptive of Major Variables

Table 2 shows descriptive statistics for each variable. The average growth rate of GTFP in 34 industries was 0.014, the max value was 0.759, the min value was -0.878, the average intensity of regulatory policy was 1.325, the max value was 2.336, the min value was 1.224, the average level of technological innovation was 6.797, the max was 11.011, and the min value was 0.693. It can be seen that the degree of dispersion of each variable was high, and there were great differences among industries in the sample period.

Table 2. Statistical description.

Variables	Obs	Mean	Std. Dev	Min	Max
lngtfp	306	0.014	0.248	−0.878	0.759
lnregu	306	1.325	0.126	1.224	2.336
lnpat	306	6.797	1.904	0.693	11.011
lnfdi	306	4.907	1.463	−2.075	7.569
lnr&d	306	13.267	1.688	7.284	16.595
lnscale	306	9.592	1.006	6.907	11.423
lnfixed	306	7.710	1.060	4.765	9.916
ownship	306	0.233	0.275	0.003	0.995

5. Empirical Results and Discussion

Data of 34 industrial subdivisions from 2007 to 2015 were used as samples for the econometric test. The Hausman endogeneity test was passed before the estimation (see Table 3). At the same time, the Hausman test results for the fixed effect and random effect suggest that the fixed effect model was appropriate. Moreover, the "xtscc, fe" command was used to weaken the influence of heteroscedasticity and cross-sectional correlation on regression results [49], while the employment of advanced panel cointegration techniques did not make sense because of a relatively short N [50,51].

Table 3. The results of the Hausman endogeneity test.

	(b)	**(B)**	**(b-B)**	**Sqrt(diag(V_b-V_B))**
	iv	ols	Difference	S.E.
lnpat	0.0702411	0.0611268	0.0091142	0.0143294
lnregu1	0.2940049	0.2732976	0.0207074	0.0258318
lnfdi	−0.0465185	−0.0375678	−0.0089508	0.007024
lnscale	0.1618421	0.1481324	0.0137098	0.0117822
lnfixed	0.0180962	0.0100492	0.008047	0.0105827
lnrd	−0.1615578	−0.1452828	−0.016275	0.0149395
_cons	−0.1781736	−0.150001	−0.0281726	0.1095481

b = consistent under Ho and Ha; obtained from ivreg2, B = inconsistent under Ha, efficient under Ho; obtained from regress, chi2(7) = (b-B)'[(V_b-V_B)^(-1)] (b-B) = 6.12, Prob>chi2 =0.5260.; The model fitted on these data meets the assumptions of the Hausman test.

5.1. Full Sample Analysis

In Table 4, Equation (1) examines the total effects of regulations on GTFP. It can be seen that the coefficient of regulations intensity was positive (0.102). With the rising of regulation intensity, the growth of GTFP in industrial industry was significantly promoted, which is consistent with Hypothesis 2. Equation (2) is the effect of regulations on the output of technical innovation of intermediary variables, and the coefficient is significantly positive (0.378). Environmental policy stimulates technological innovation of industrial industry, which confirms Hypothesis 1. The coefficients of environmental regulation and innovation in Equation (3) were statistically positive, which could explain the intermediary effect. Environmental policy had a direct effect on GTFP (0.0853), and at the same time it produced a positive intermediary effect (0.0283) through technological innovation. Therefore, environmental regulation not only directly affected the green total factor productivity but also affected the green total factor productivity through the mediating effect of technological innovation, which verified Hypothesis 3.

From the control variables, the level of foreign investment had a statistically positive impact on GTFP. Foreign investment improved the host country's clean technology level through the "pollution halo" effect, thereby improving the host country's environmental level, and significantly affecting Chinese industrial sustainable transition and green development. The industry scale positively influenced GTFP. The larger the scale, the more powerful the enterprises developed green R&D. In the face of the same environmental regulation intensity, larger enterprises were likely to motivate the enterprises to develop environmental protection technology, so as to gain competitive advantage in economic transformation. The degree of capital deepening had a negative impact on GTFP, which indicates that the rapid accumulation of industrial capital dominated by direct investment mainly relies on extensive industrial scale expansion to achieve economic development, leading to a sharp drop in environmental quality. Technical innovation positively influenced GTFP. As the patent number increased, the innovative capability of enterprises grew, thus driving the improvement of green production efficiency.

Table 4. Full sample regression.

	(1)	(2)	(3)
	lngtfp	**lnpat**	**lngtfp**
lnregu	0.102 ***	0.378 ***	0.0853 ***
	(2.93)	(3.30)	(2.68)
lnfdi	0.0519 ***	0.00126	0.0526 ***
	(2.29)	(0.03)	(2.36)
lnscale	0.746 ***	0.359 ***	0.715 ***
	(11.42)	(2.17)	(11.99)
lnfixed	−0.496 ***	0.336 ***	−0.517 ***
	(−19.34)	(11.92)	(−17.22)
lnr&d		0.767 ***	
		(11.13)	
ownship		−1.614 *	
		(−1.48)	
lnpat			0.0283 ***
			(2.87)
_cons	−3.703 ***	−9.553 ***	−3.416 ***
	(−11.08)	(−9.91)	(−11.63)
N	306	306	306

t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Since there were great industrial differences in product characteristics and production processes, different industries differed in their responses to environmental regulation, in terms of their different pollution levels and different technological levels. Therefore, industries that were classified referred to the difference of pollution degree and technology level (see Appendix A). Furthermore, we investigated the impact of regulations and technological innovation on GTFP on the basis of classification.

5.2. Results of Industries with Different Pollution Levels

Due to the industrial difference in the pollution degree, the effects of environmental policies on GTFP and intermediary effects of technological innovation could also lead to different results. According to industries under different pollution degrees, the effect of regulations on GTFP in clean industries and pollution-intensive industries was positive (see Table 5). The total effect coefficient of clean industries was statistically positive (0.132), the direct effect coefficient was also statistically positive (0.123), the elasticity of regulations on technical innovation was 0.282, and the impact coefficient of technological innovation on total green productivity was 0.0287. The total effect coefficient of pollution-intensive industries was positive (0.15) but not significant. The direct effect coefficient was also positive (0.108) while not significant. The impact coefficient of regulations on technical innovation was 0.192. The coefficient of technological innovation on GTFP was significantly positive (0.0347). Therefore, environmental regulation in clean industries played a significant role in innovative activities and GTFP but the relationship was not significant in pollution-intensive industries. For this respect, the environmental regulation intensity of the two industries was compared. Although the total expenditure on pollution control was much higher in the pollution-intensive industries than in the clean industries, the emission cost of pollutants per unit in the clean industries was higher than that in the pollution-intensive industries. In clean industries and pollution-intensive industries, the impact of technological innovation on GTFP was statistically positive.

The sunk cost of clean industries was found to be relatively low in the production process, and the renewal and transformation of technology and equipment was also relatively easy. As such, their R&D and innovation strategies could be adjusted according to meeting the environmental regulation and consequently improve the GTFP. The cost of environmental technology in pollution−intensive industries as found to be relatively high, and the technological level of enterprises was also difficult to change with the variation

of environmental regulation. Therefore, the impact of environmental regulation on GTFP were tested without significance in these specific industries.

Table 5. Regression with different pollution levels.

	Clean Industries			Pollution−Intensive Industries		
	(1)	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
	lngtfp	**lnpat**	**lngtfp**	**lngtfp**	**lnpat**	**lngtfp**
lnregu	0.132 ***	0.282 ***	0.123 ***	0.15	0.192	0.108
	(2.73)	(2.13)	(2.74)	(1.38)	(0.31)	(0.85)
lnfdi	0.0237 ***	0.137 ***	0.0208 ***	0.103 ***	−0.194 **	0.109 ***
	(6.38)	(3.28)	(4.55)	(2.4)	(−2.10)	(2.79)
lnscale	0.762 ***	−0.188	0.747 ***	0.877 ***	1.072 ***	0.819 ***
	(53.65)	(−0.92)	(51.4)	(8.02)	(2.96)	(7.68)
lnfixed	−0.457 ***	0.468 ***	−0.487 ***	−0.674 ***	0.0771	−0.687 ***
	(−41.21)	(4.56)	(−45.27)	(−15.99)	(0.45)	(−13.80)
lnr&d		0.886 ***			0.644 ***	
		(5.54)			(4.06)	
ownship		−4.339 ***			−0.387	
		(−3.79)			(−0.28)	
lnpat			0.0287 ***			0.0347 ***
			(2.42)			(2.79)
_cons	−4.063 ***	−6.631 ***	−3.875 ***	−3.875 ***	−12.24 ***	−3.403 ***
	(−38.82)	(−8.27)	(−39.93)	(−7.81)	(−7.22)	(−7.11)
N	153	153	153	153	153	153

t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5.3. Results of Industries with Different Technical Levels

In order to further test the heterogeneity of direct and indirect impacts of regulations on green performance under different technological levels, the situations of industrial different technology level (as shown in Table 6) were compared and analyzed. The findings suggested that significant differences between environmental regulation and GTFP are shown in high-tech industries, as well as low- and medium-tech industries.

Table 6. Regression of industries with different technical levels.

	High-Tech Industries			Low- and Medium-Tech Industries		
	(1)	**(2)**	**(3)**	**(1)**	**(2)**	**(3)**
	lngtfp	**lnpat**	**lngtfp**	**lngtfp**	**lnpat**	**lngtfp**
lnregu	0.374 ***	0.628 *	0.345 ***	0.0726 *	0.391 ***	0.0562
	(3.21)	(1.67)	(3.29)	(1.59)	(2.6)	(1.33)
lnfdi	0.0199	0.282 ***	−0.000963	0.0491 ***	−0.0327	0.0506 **
	(0.57)	(3.52)	(−0.02)	(2.25)	(−0.69)	(2.41)
lnscale	0.573 ***	−0.606 ***	0.512 ***	0.835 ***	0.490 ***	0.806 ***
	(9.76)	(−3.70)	(15.51)	(14.87)	(2.62)	(15.1)
lnfixed	−0.364 ***	0.180 ***	−0.405 ***	−0.568 ***	0.347 ***	−0.589 ***
	(−16.34)	(5.02)	(−13.34)	(−29.46)	(10.55)	(−27.72)
lnr&d		1.373 ***			0.689 ***	
		(14.53)			(10.77)	
ownship		−3.192 ***			−1.48	
		(−3.53)			(−1.17)	
lnpat			0.0624 ***			0.0268 ***
			(2.39)			(3.12)
_cons	−3.447 ***	−9.067 ***	−2.865 ***	−3.843 ***	−9.839 ***	−3.562 ***
	(−19.25)	(−7.60)	(−18.30)	(−11.84)	(−8.87)	(−11.31)
N	90	90	90	216	216	216

t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

The total effect coefficient of high−tech industries was 0.374, the total effect coefficient of low- and medium-tech industries was 0.0726, the direct effect coefficient of high- tech industries was 0.345, and the direct effect coefficient of low- and medium-tech industries was 0.0562, none of which were significant. Meanwhile, in high-tech industries, the impact coefficient of regulations on technical innovation was 0.628 and the effects of technological innovation on GTFP was 0.0624, whereas in low- and medium-tech industries, the impact of regulations on technical innovation was 0.391, and the impact elasticity of technological innovation on GTFP was 0.0268. Thus, in high-tech industries, the direct influences of regulations on GTFP and the intermediary effect through technical innovation were large. In the low- and medium-tech industries, technological innovation played a full moderating part in the relation of regulations and GTFP.

The comparisons show that environmental regulation in high-tech industries had a bigger influence on technological innovation and GTFP than in low- and medium-tech industries. Similarly, technical innovation had a larger positive effect on GTFP. Therefore, both the direct and indirect effects of regulations on GTFP in high-tech industries were greater than those in low- and medium-tech industries.

5.4. Robustness Test

To maintain the robustness of the conclusion, the pollution abatement expenditure was used as an indicator for regulations to test the stability of the relations of regulatory policies, technical innovation, and GTFP [52–54]. The results of total sample analysis show that the direct effect of environment-related regulations on GTFP was promotive (0.0376). The regression coefficient of regulations on technical innovation as significantly positive (0.0566). Technical innovation positively affected the GTFP (0.0287). The direction of coefficients and overall significance were consistent with the above results (see Table 7).

Table 7. Results of robustness test.

	(1)	(2)	(3)
	lngtfp	**lnpat**	**lngtfp**
lnpace	0.0392 ***	0.0566 *	0.0376 ***
	(3.62)	(1.65)	(3.39)
lnfdi	0.0535 ***	0.00191	0.0543 ***
	(2.37)	(0.05)	(2.45)
lnscale	0.720 ***	0.324 **	0.689 ***
	(10.12)	(2.03)	(10.73)
lnfixed	−0.489 ***	0.331 ***	−0.510 ***
	(−17.60)	(8.85)	(−15.76)
lnr&d		0.783 ***	
		(10.46)	
ownship		−1.730 *	
		(−1.53)	
lnpat			0.0287 ***
			(3.02)
_cons	−3.848 ***	−9.525 ***	−3.560 ***
	(−11.25)	(−8.67)	(−11.59)
N	306	306	306

t statistics in parentheses, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

6. Conclusions and Policy Implications

6.1. Conclusions

(1) To achieve the dual goals of environmental protection and high-quality development, it should not only rely on total factor productivity to achieve innovative growth but also solve environmental problems to reduce the pressure of emission reduction [55,56]. Theory and experience show that technological innovation is the key driving force for achieving long-term green economic development under the con-

straints of environmental policies. Therefore, is technological innovation an effective way to solve problems of ecological civilization construction and economic quality upgrading, whole also realizing environmental protection and high-quality economic development? Based on the panel data of 34 industries in China from 2007 to 2015, this paper firstly calculated the green total factor productivity (GTFP) as a proxy variable to determine the quality of economic development through the super-slack-based measure model, and then analyzed the impact of environmental regulation and technical innovation on the GTFP by making use of the mediation effect model. In terms of the overall change range of GTFP, the average growth rate of GTFP was 4.6%. Among them, the efficiency of green technology decreased by 2.8%, and the progress of green technology increased by 10.5%. Therefore, the growth of GTFP mainly came from the progress of green technology. Environmental policy had a direct effect on GTFP (0.0853), and at the same time, it produced a positive intermediary effect (0.0283) through technological innovation. The effect of environmental regulation on GTFP shows industrial heterogeneity.

(2) The growth of industrial GTFP mainly came from the change of technological progress. In all, the average GTFP of China's industrial subdivisions was 1.046 over the period of 2007 to 2015, of which the average green technology efficiency was 0.972 and the average green technology progress was 1.105. From the Malmquist productivity index and its decomposition, the average annual speed of GTFP was 1.3%, the average annual growth rate of green technical efficiency was −0.1%, and the average annual growth rate of green technical progress was 1.9%. It can be seen that green technical advance was the principal driving force of industrial GTFP.

(3) The direct impact of regulations on GTFP was positive, which indicates that pollution control and productivity improvement had the potential to be a win–win. Among them, in the clean industries and high-tech industries, environmental policy played a significant part in inducing technological innovation, while positive but not significant in the pollution-intensive industries and low- and medium-tech industries.

(4) Environmental regulation played an essential role in improving the innovative activities that confirmed the existence of Porter's hypothesis. This shows that the compensation effect of regulations on technical innovation was greater than the offset effect by improving the technological level of pollution control and production, resulting in the promotion of technical innovation. In clean industries, high-tech industries, and low- and medium-tech industries, the effect of regulations on technological innovation was statistically positive, i.e., positive but not significant in the pollution-intensive industries.

(5) The intermediary role of technological innovation influenced the relations between regulations and total factor productivity. Environmental regulation not only directly affected GTFP but also promoted the improvement of GTFP through the intermediary effects of technical innovation. In the clean industries and high-tech industries, the intermediary role of technological innovation was particularly evident, and low- and medium-tech industries was a complete intermediary. In pollution-intensive industries, technological innovation had a great impact on GTFP, which suggests that technological innovation is a principal driving factor in strengthening the coordination of China's industrial economy and environment to achieve green growth. Therefore, in order to achieve a "win–win" situation of economic development and environmental quality improvement, the Chinese government should devote its efforts to elaborating upon environmental policies and improving subsidies for green technology innovation.

6.2. Policy Implications

Accordingly, the policy recommendations are proposed as follow:

(1) Perfect the environmental regulation system and formulate appropriate environmental regulation measures [57]. Whether enterprises can be encouraged to innovate in the environmental technology should be taken into account for the design of environmental regulation in China. Combining the "command−control" regulatory tools with the "market incentive" regulatory tools, enterprises can be guided to take initiative to undertake the responsibility of energy saving and pollution abatement, realizing the innovative compensation effects of regulatory policy. For heavy polluting industries, the control type of environmental regulation should be adopted to reduce pollution emissions; for clean industries and technology-intensive industries, emission trading measures can be flexibly used to encourage enterprises to innovate in pollution control technology and production technology, and improve the ability of pollution control and production efficiency.

(2) Increase public subsidies for environmental R&D and improve enterprises' ability to innovate in environmental technology domain. Technological innovation positively affects GTFP but with uncertainty and high risk. If enterprises invest too much in environmental technological innovation, they may squeeze out production-oriented investment, which is not beneficial to the enhancement of enterprise competitiveness.

(3) Eliminate enterprises with demanding energy consumption and pollution, and encourage green transition and technological progress of firms. In pollution-intensive industries and low- and medium-tech industries, the positive effect of regulations on GTFP is not obvious, but technological innovation has a great influence on GTFP. Therefore, accelerating the transformation of heavy polluting enterprises to clean enterprises and low-tech enterprises to high-tech enterprises can strengthen the positive impact of regulations and technical innovation on GTFP.

Due to the limitations of the research scope, length, and data availability, this study still needs to be improved. The impact of environmental regulation and technological innovation on the green total factor productivity index may show firm heterogeneity or regional heterogeneity. The relationship between environmental regulation, technical innovation, and GTFP changes when the data samples are divided according to the heterogeneity of firms or regions. Therefore, it is of great importance to study the effect of environmental regulation and technology innovation on GTFP from an enterprise perspective or from a regional aspect.

Appendix A

1. Industry codes (34): (1) mining and washing of coal; (2) extraction of petroleum and natural gas; (3) mining and processing of ferrous metal ores; (4) mining and processing of non-ferrous metal ores; (5) mining and processing of non-metal ores; (6) processing of food from agricultural products; (7) manufacture of foods; (8) manufacture of wine, drinks and refined tea; (9) manufacture of tobacco; (10) manufacture of textile; (11) manufacture of textile wearing and apparel; (12) manufacture of leather, fur, feather and related products and footwear; (13) processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products; (14) manufacture of furniture; (15) manufacture of paper and paper products; (16) printing, reproduction of recording media; (17) manufacture of articles for culture, education and sport activity; (18) processing of petroleum, coking, processing of nuclear fuel; (19) manufacture of raw chemical materials and chemical products; (20) manufacture of medicines; (21) manufacture of chemical fibers; (22) manufacture of rubber and plastic; (23) manufacture of non-metallic mineral products; (24) smelting and pressing of ferrous metals; (25) smelting and pressing of non-ferrous metals; (26) manufacture of metal products; (27) manufacture of general purpose machinery; (28) manufacture of special purpose machinery; (29) manufacture of transport equipment; (30) manufacture of electrical machinery and equipment; (31) manufacture of computers, communication, and other electronic equipment; (32) manufacture of measuring instrument; (33) production and supply of electric power and heat power; (34) production and supply of gas.

2. Classification results according to pollution degree: clean industries (17 industries): extraction of petroleum and natural gas; manufacture of tobacco; manufacture of textile wearing and apparel; manufacture of leather, fur, feather and related products, and footwear; processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products; manufacture of furniture; printing, reproduction of recording media; manufacture of articles for culture, education and sport activity; manufacture of medicines; manufacture of rubber and plastic; manufacture of metal products; manufacture of general purpose machinery; manufacture of special purpose machinery; manufacture of transport equipment; manufacture of electrical machinery and equipment; manufacture of communication equipment, computers and other electronic equipment; manufacture of measuring instrument. pollution−intensive industries (17 industries): mining and washing of coal; mining and processing of ferrous metal ores; mining and processing of non−ferrous metal ores; mining and processing of non−metal ores; processing of food from agricultural products; manufacture of foods; manufacture of wine, drinks and refined tea; manufacture of textile; manufacture of paper and paper products; processing of petroleum, coking, processing of nuclear fuel; manufacture of raw chemical materials and chemical products; manufacture of chemical fibers; manufacture of non-metallic mineral products; smelting and pressing of ferrous metals; smelting and pressing of non−ferrous metals; production and supply of electric power and heat power; production and supply of gas.

3. Classification results according to technical level: high-tech industries (10 industries): manufacture of raw chemical materials and chemical products; manufacture of medicines; manufacture of chemical fibers; manufacture of metal products; manufacture of general purpose machinery; manufacture of special purpose machinery; manufacture of transport equipment; manufacture of electrical machinery and equipment; manufacture of computers, communication, and other electronic equipment; manufacture of measuring instrument. low- and medium-tech industries (24 industries): mining and washing of coal; extraction of petroleum and natural gas; mining and processing of ferrous metal ores; mining and processing of non-ferrous metal ores; mining and processing of non-metal ores; processing of food from agricultural products; manufacture of foods; manufacture of wine,

drinks and refined tea; manufacture of tobacco; manufacture of textile; manufacture of textile wearing and apparel; manufacture of leather, fur, feather and related products and footwear; processing of timber, manufacture of wood, bamboo, rattan, palm, and straw products; manufacture of furniture; manufacture of paper and paper products; printing, reproduction of recording media; manufacture of articles for culture, education and sport activity; processing of petroleum, coking, processing of nuclear fuel; manufacture of rubber and plastic; manufacture of non-metallic mineral products; smelting and pressing of ferrous metals; smelting and pressing of non-ferrous metals; production and supply of electric power and heat power; production and supply of gas.

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