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Research On Green Total Factor Productivity Of The Petrochemical Industry From The Perspective Of The Chinese Industrial Sector

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Abstract:
This study employs the approach proposed by Oh (2010) to measure the green total factor productivity (GTFP) growth of China's industrial sectors, with a focus on the petrochemical industry, using the directional distance function (DDF) and the global Malmquist-Luenberger (GML) productivity index. The study considers the factors of energy consumption and carbon emissions and examines the impacts of labor input, capital stock, CO2 emissions, energy consumption, and output level on the GTFP of the petrochemical industry from the perspective of China's industrial sectors, based on data from 35 sub-industries of China's industrial sectors during 2001-2019. The analysis of the petrochemical industry from the aspects of time span, industry perspective, and GTFP composition reveals that the decline in GTFP of the petrochemical industry has a negative effect on the growth of China's GTFP. The improvement of GTFP in the petrochemical industry is attributed to the growth of technological progress. The study finds that endowment structure factors have a significant negative correlation with GTFP and technical efficiency, but no significant positive correlation with technological progress. The R&D level factor has a significant positive effect on GTFP and technical efficiency but a non-significant negative effect on technological progress. The energy structure factor has a significant negative impact on GTFP and a non-significant negative impact on its decomposition items. Foreign direct investment has a significant negative effect on GTFP and technological progress but a significant positive effect on technical efficiency. Based on the results, the study proposes green development suggestions, including increasing technological innovation, digital transformation, and industrial upgrading, introducing foreign or private capital, using new clean energy technologies, and reducing the proportion of fossil energy.

Keywords: *Chinese industry,Petrochemical industry, Green development,Green total factor productivity.*

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I. Introduction

The Chinese petrochemical industry has a complete industrial system, which is traditionally divided into oil and gas extraction (OGE), petroleum refining, coking, and nuclear fuel processing (PCP), chemical raw materials and chemical product manufacturing (CMC), chemical fiber manufacturing (MFP), and rubber and plastic product manufacturing (RPP). The development of China's petrochemical industry has been characterized by extensive growth with high energy consumption, high input, high pollution, and low output. However, with technological progress and the development of new energy sources in recent years, the energy efficiency of the petrochemical industry has improved, but its energy consumption still accounts for a relatively high proportion of the entire industry. In 2016, the energy consumption of the petrochemical industry reached 78.5 million tons of standard coal, accounting for 26.86% of the energy consumption of the entire industry. At the same time, the petrochemical industry is also a major industry for carbon emissions, accounting for about 3% of the national carbon emissions in 2016. From 2001 to 2019, the total output value of the petrochemical industry continued to steadily increase, while energy consumption and carbon emissions during production also increased. The key to achieving green development of the petrochemical industry is to improve its environmental efficiency, particularly in terms of low energy consumption and low emissions, which can be achieved by increasing the petrochemical industry's green total factor productivity (TFP). This paper analyzes the green TFP of the petrochemical industry from the perspective of the Chinese industrial sector and its influencing factors and provides recommendations for achieving green development in the petrochemical industry.

II. Literature Review

The measurement of total factor productivity (TFP) can be broadly classified into two categories: parametric and non-parametric methods. Parametric methods, such as the Solow residual and stochastic frontier production function, can further determine the production mode in economic growth. Non-parametric methods mainly refer to Data Envelopment Analysis (DEA), which requires the construction of a production frontier and uses mathematical methods such as linear programming to measure TFP. The DEA-Malmquist index method further decomposes TFP into technical progress and technical efficiency indices, providing insight into the driving force behind productivity growth. The method proposed by Swedish scholar Malmquist, which is the initial form of the Malmquist index, involves the ratio of scaling factors[1].The corresponding distance function was proposed by Perlmutter in his study of production functions[2].Farrell mentioned the envelopment analysis method[3].American operations researchers (Charnes et al.) used linear programming to evaluate efficiency, which is the data envelopment analysis method and established input-oriented and constant returns to scale models[4].Banker et al. extended the constant returns to scale model to variable returns to scale models[5].Caves et al. employed the Marquardt index analysis method in their research in the production field[6].Färe et al. combined DEA with the Malmquist index method, further decomposing the index into technical progress and technical efficiency indices[7].Ray et al. modified the model and proposed the definition of the generalized Malmquist index[8, 9].In recent years, many scholars (Yu et al., 2008; Song et al., 2012; Emrouznejad & Yang, 2018; Feng et al., 2018) have used DEA in the analysis of green productivity in different regions and industries[10-13].Foreign scholar Young calculated China's TFP (Young, 2011; Young, 2012; Young, 2013)[14-16],and Perkins calculated the growth rate of China's TFP (Perkins, 2014)[17].

The existing literature on China's total factor productivity (TFP) does not fully and accurately reflect the country's economic growth due to the omission of environmental factors[18].As research progresses, scholars both in China and abroad have incorporated environmental factors into the study of China's TFP[19-21].While most of the literature includes multiple indicators of environmental factors such as wastewater, exhaust gas, and solid waste, this comprehensive approach makes it difficult to highlight the development of specific environmental indicators and provide policy recommendations due to the different characteristics of various pollutants.

This literature review and analysis revolve around total factor productivity (TFP), with an increasing number of scholars shifting their attention toward the study of green TFP. The research has focused mainly on the industry sector, examining single-factor and multi-factor measures of green TFP, as well as the analysis of influencing factors such as those done by Fujii et al[22-24].Similarly, studies have been carried out in the agricultural sector by Coelli et al[25-27].Scholars such as Chen have used the directional distance function (DDF) and global Malmquist-Luenberger (GML) productivity index to measure the green TFP of China's industrial sectors, provinces, cities, and ports, with a corresponding analysis of the factors influencing the measurements[28-33].Su measured the energy efficiency levels of 30 Chinese provinces from 2000 to 2017 [34].Li et al. measured the green TFP of each industrial sector and found that its growth mainly relied on technological progress rather than technological efficiency[35].Yao et al. measured the green TFP using the super-SBM model, including green technological innovation areas in city industry, manufacturing, and China's A-share listed companies and analyzed the mechanism of influence[36-38].Zeng analyzed the green technological innovation (GTI) levels of 30 Chinese provinces using a spatial econometric model and panel threshold model, combined with the slack-based measure (SBM) and Global Malmquist-Luenberger (GML) index [39].Shen used the SBM-GML index method to measure the industrial green TFP, utilizing a two-way fixed-effects model, instrumental variable method, and other methods to analyze influencing factors [40].Zhao used the SBM-GML index model to calculate the green TFP, assessing the green development level of the Yellow River Basin and analyzing the influencing factors using the GMM model[41].Xie et al. combined the EBM and GML productivity indices to calculate the TFP, while Li et al. measured the ETFEE and ETFE of 283 prefecture-level cities in China and their decomposition, studying the influencing factors[42].Xie incorporated carbon emissions and agricultural non-point source pollution constraints into the input-output indicator system, measuring the changes in China's land use efficiency and TFP[43].Jiang used the relaxation-based model and the global Malmquist-Luenberger index to study the carbon emission performance of the transportation industry [44].Wang used the unexpected output SE-SBM model, GML index, and grey relational model to analyze the dynamic evolution trend and driving factors of high-quality development of China's construction industry [45]. Yue used the DDF and GML index method to calculate the China Industrial Green Transformation (IGT) index and analyzed its evolution and spatial distribution characteristics [46].Zheng evaluated China's GTFEE using non-radial data envelopment analysis (DEA), considering climate and air pollution caused by energy use[47].

The literature review reveals that research on industry-level green total factor productivity (GTFP) is mainly focused on large industries such as manufacturing and agriculture, with limited studies that specifically investigate GTFP in the industry (PI) and its sub-industries. Moreover, the literature suggests that the selection of factors affecting GTFP should be targeted according to the characteristics of the industry. Therefore, further research is needed to explore the GTFP of the PI and its sub-industries and to identify the relevant factors affecting GTFP based on the specific features of the industry.

III. Model construction

With the increasing prominence of environmental issues and the proposal of green development, more and more scholars have incorporated energy consumption as an input and carbon emissions as a bad output into the analysis framework of green total factor productivity (GTFP), using data envelopment analysis (DEA) to calculate GTFP for different regions and industries. This study follows the research approach of Oh (2010), adopting directional distance function (DDF) and global Malmquist-Luenberger (GML) productivity index to measure the growth of GTFP in China, with the contemporaneous production technology defined as $\mathrm{P^t}(\times^{\mathrm{t}}) = \{\mathrm{y^t}, \mathrm{z^t} | \mathrm{x^t}(\mathrm{y^t}, \mathrm{z^t})\}, \mathrm{t} = 1, \cdots, \mathrm{T}$, and aimed at providing a reference technology set for each observational unit at time t. The union of all contemporaneous production technology sets is defined as the global production technology set: $\mathrm{P^G}(\mathrm{x}) = \mathrm{P^1}(\mathrm{x^1}) \cup \mathrm{P^2}(\mathrm{x^2}) \cdots \mathrm{P^T}(\mathrm{x^T})$, which encompasses all observational units and all time periods. Based on the production technology set $\mathrm{P^G}(\mathrm{x})$, the GML productivity index can be defined as :

$$\mathrm{GML}_{\mathrm{t}}^{\mathrm{t+1}}(\mathrm{x^t}, \mathrm{y^t}, \mathrm{z^t}; \mathrm{x^{t+1}}, \mathrm{y^{t+1}}, \mathrm{z^{t+1}}) = \frac{1 + \vec{D}_0^{\mathrm{t}}(\mathrm{x^t}, \mathrm{y^t}, \mathrm{z^t}; \mathrm{y^t}, -\mathrm{z^t})}{1 + \vec{D}_0^{\mathrm{t+1}}(\mathrm{x^{t+1}}, \mathrm{y^{t+1}}, \mathrm{z^{t+1}}; \mathrm{y^{t+1}}, -\mathrm{z^{t+1}})} \quad (1)$$

Only one global production technology set was used throughout the entire study period, avoiding the flaws caused by the geometric mean form, and the GML meets the transitivity requirement. In addition, using a global production technology set can also avoid the flaw of linear programming having no feasible solution. The GML can be decomposed into two parts: the productivity index and the technical progress index.

$$\begin{aligned}\mathrm{GML}_t^{t+1} &= \frac{1+\vec{D}_0^G(x^t,y^t,z^t;y^t,-z^t)}{1+\vec{D}_0^G(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})} \\ &= \frac{1+\vec{D}_0^t(x^t,y^t,z^t;y^t,-z^t)}{1+\vec{D}_0^{t+1}(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})} \\ &\times \frac{\left[1+\vec{D}_0^G(x^t,y^t,z^t;y^t,-z^t)\right]/\left[1+\vec{D}_0^t(x^t,y^t,z^t;y^t,-z^t)\right]}{\left[1+\vec{D}_0^G(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})\right]/\left[1+\vec{D}_0^{t+1}(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})\right]} \\ &= \frac{\mathrm{TE}^t(x^t,y^t,z^t;y^t,-z^t)}{\mathrm{TE}^{t+1}(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})} \times \frac{\mathrm{TPG}^{G,t}(x^t,y^t,z^t;y^t,-z^t)}{\mathrm{TPG}^{G,t+1}(x^{t+1},y^{t+1},z^{t+1};y^{t+1},-z^{t+1})} \\ &= \mathrm{GMLTC}_t^{t+1} \times \mathrm{GMLEC}_t^{t+1} \qquad (2)\end{aligned}$$

In the formula, an increase in GML indicates an improvement in productivity. If GML is greater than 1, it indicates an increase in the green total factor productivity (GTFP) of the sub-industries of PI; if GML is less than 1, it indicates a decrease in GTFP and a setback in productivity; if GML equals 1, it means that GTFP remains unchanged. GMLEC serves as the global technical efficiency change index, indicating the distance between the production decision unit and the production frontier during the observation period. If the GMLEC index is greater than 1, it means that the industries are closer to the production frontier, and the improvement in technical efficiency promotes the growth of GTFP. Conversely, it indicates a decline in technical efficiency and a decrease in production efficiency. GMLTC is the global technological progress change index, indicating the distance between the industry's production frontier and the global production frontier during the observation period. If the GMLTC index is greater than 1, it means that the industry's production frontier is closer to the global production frontier, and the level of technological progress or high-tech innovation has driven the growth of GTFP. Conversely, it indicates a decline in technical progress or insufficient technological innovation.

IV. Variable Selection and Data Sources

Based on the classification standard of China's industrial two-digit industry in GB/T 4754-2017, Due to the need for data availability and accuracy, artisanal and other manufacturing industries, other mining industries, waste, and scrap recycling industries were excluded, and 35 sub-industries of Chinese industry were selected for the study.

The input variables selected were labor force, capital stock, and energy consumption, with industrial output value as the expected output and carbon emissions as the non-expected output. The specific data for the relevant variables in this study were mainly sourced from the "China Statistical Yearbook," "China Energy Statistical Yearbook," "China Industrial Economic Statistical Yearbook," and "China Chemical Industry Statistical Yearbook," among others. Labor input is measured by the number of employed persons. Capital stock was measured by the net value of fixed assets in China's industrial sector by two-digit industry. Total energy consumption was measured by the industry's total energy consumption. Industrial output value was measured by the industrial total output value of the two-digit industry. The data were adjusted to the constant price of 1998. The carbon emissions were estimated for Chinese industries using the carbon emissions accounting method recommended by the IPCC. The calculation formula is as follows:

$$C = \sum_{i=1}^{n} E_i \times NCV_i \times CEF_i \times COF_i \times \frac{44}{12} \qquad (3)$$

In the formula, C represents the amount of carbon dioxide emissions, E represents the consumption of different types of fossil fuels and other energy sources, F represents the type of fossil fuel energy, NCV represents the net calorific value, which is the average lower heating value of fossil fuel energy, CEF represents the carbon emission factor, COFi represents the carbon oxidation factor. The COFi value used in this study comes from the Energy Research Institute of the National Development and Reform Commission of China. 44/12 represents the ratio of the molecular weights of carbon and carbon dioxide, and the product of CEF, COF, and 44/12 is sometimes referred to as the carbon dioxide emission factor.

Regarding the selection of energy consumption of fossil fuels and other sources, the final consumption of 17 types of fossil fuel energy sources recorded in the "China Energy Statistical Yearbook" was used. The net calorific value of fossil fuel energy sources was set based on reports such as the "China Energy Statistical Yearbook" and the "2006 IPCC National Greenhouse Gas Inventory Preparation Guidelines", and it was assumed that they remained constant during the study period. Due to China's lower energy utilization efficiency compared to international standards, this study did not adopt the default carbon oxidation factor recommended by the IPCC, and the COF value used in this study comes from the Energy Research Institute of the National Development and Reform Commission of China.

V. Green Total Factor Productivity Calculation and Analysis

Based on the input-output data of China's industry from 2001 to 2019, with carbon emissions as the undesirable output, the Green Total Factor Productivity (GML) index of each industry in China's industry from 2001 to 2019 was calculated, and further decomposed into the Technical Efficiency Index (GMLEC) and the Technical Progress Index (GMLTC). For ease of expression, the end year of adjacent years is used to represent adjacent times, such as 2001 to 2002 abbreviated as 2002.

Calculation Results

Table 2 Green Total Factor Productivity and its Decomposition Items of China's Industry from 2001 to 2019.

Industrial sectors	GML	GMLEC	GMLTC
(1) Mining Industry	**0.9963**	**1.0013**	**1.0015**
Coal mining and washing industry	1.0044	1.0173	1.0036
Oil and gas extraction industry（OGE）*	0.9971	0.9921	1.0076
Black metal ore mining and dressing industry	0.9816	0.9823	0.9997
Non-ferrous metal ore mining and dressing industry	0.9983	1.0020	1.0001
Non-metallic mineral mining and dressing industry	1.0004	1.0128	0.9963
(2) Manufacturing Industry	**0.9964**	**1.0001**	**0.9969**
Agricultural and sideline food processing industry	0.9948	1.0035	0.9912
Food manufacturing industry	0.9920	0.9995	0.9929
Beverage manufacturing industry	0.9971	1.0103	0.9863
Tobacco products industry	1.0004	1.0000	1.0004
Textile industry	0.9923	0.9965	0.9965
Textile, clothing, footwear, and hat manufacturing industry	0.9832	0.9872	0.9968
Leather, fur, feather, and their products industry	0.9934	0.9973	0.9964
Wood processing and bamboo, rattan, palm, and straw products industry	0.9875	0.9904	1.0009
Furniture manufacturing industry	0.9816	0.9857	0.9966
Papermaking and paper products industry	0.9954	0.9980	0.9976
Printing and reproduction of recording media	0.9920	0.9971	0.9991

Sports, cultural and educational supplies manufacturing industry	0.9844	0.9916	0.9929
Petroleum processing, coking, and nuclear fuel processing industry(PCP)*	1.0026	1.0000	1.0026
Chemical raw materials and chemical product manufacturing industry(CMC)*	1.0026	1.0033	0.9997
Pharmaceutical manufacturing industry	0.9946	1.0026	0.9921
Chemical fiber manufacturing industry(MFP)*	0.9972	0.9958	1.0029
Rubber products and plastic products industry(RPP)*	0.9929	0.9994	0.9940
Non-metallic mineral product manufacturing industry	1.0016	0.9992	1.0040
The black metal smelting and rolling processing industry	1.0030	1.0000	1.0030
The non-ferrous metal smelting and rolling processing industry	1.0123	1.0174	0.9956
Metal products industry	0.9911	0.9984	0.9925
General equipment manufacturing industry	0.9962	1.0037	0.9927
Special equipment manufacturing industry	1.0012	1.0054	0.9968
Transportation equipment manufacturing industry	1.0126	1.0144	0.9985
Electrical machinery and equipment manufacturing industry	1.0023	1.0054	0.9970
Communication, computer, and other electronic equipment	0.9990	1.0000	0.9990
manufacturing industry	0.9984	1.0006	0.9983
Instrumentation and cultural, office machinery manufacturing industry	1.0016	0.9992	1.0040
(3) Electricity and Other Supply Industries	**1.0080**	**0.9997**	**1.0093**
Electricity, heat production, and supply industry	1.0214	1.0063	1.0157
Gas production and supply industry	0.9939	0.9924	1.0042
Water production and supply industry	1.0086	1.0003	1.0081
(4) Petrochemical industry（PI）	**0.9985**	**0.9981**	**1.0013**
Chinese industry	**0.9973**	**1.0002**	**0.9986**

Remarks: Adding "*" represents the petrochemical industry sub-sector

Results Analysis

Comparison of Chinese Industrial Categories

Based on the classification of Chinese industrial sectors, a comparison of the total factor productivity index of each sub-sector was conducted to determine the productivity level of the petrochemical industry within the Chinese industrial categories.

Table 3 Total Factor Productivity Index and Its Decomposition of Chinese Industrial Categories from 2001 to 2019

Index	GML	GMLEC	GMLTC
Mining Industry	0.9964	1.0013	1.0015
Manufacturing	0.9964	1.0001	0.9969
Electricity and Power Supply	1.0080	0.9997	1.0093
Petrochemical Industry	0.9985	0.9981	1.0013
Chinese Industry	0.9973	1.0002	0.9986

In the context of China's industrial classification, the GML index suggests that the electricity supply industry is at the forefront of productivity, with an average annual growth rate of 0.8% in green total factor productivity. Conversely, the mining, manufacturing, and petrochemical industries fall behind the global productivity frontier, with the petrochemical industry ranking second in terms of GML, surpassing the overall productivity level of the Chinese industry. The ranking of the petrochemical industry is lowest in terms of GMLEC, indicating lower technological efficiency. However, in terms of GMLTC, the petrochemical industry is at the forefront of technological progress, surpassing the average level of the Chinese industry with an average annual growth rate of 0.13%. Thus, the petrochemical industry has contributed to China's technological advancement. Nonetheless, due to its lower technological efficiency, the overall technological efficiency of the Chinese industry has been affected, causing PI's green total factor productivity to regress.

Ranking of PI Sub-industries

The ranking of the green total factor productivity and its decomposition of PI sub-industries in China's industry is shown in the following table.

Table 4 Ranking of green total factor productivity and its decomposition of PI sub-industries from 2002 to 2019

PI sub-industries	GML	GMLEC	GMLTC
OGE	18	30	3
PCP	7	17	9
CMC	7	11	13
MFP	17	28	8
RPP	26	21	28

The rankings of green total factor productivity (GTFP) and its components for PI's sub-industries in the context of the Chinese industry are presented in Table 4. Among the 35 industries in the Chinese industry, OGE, PCP, and MFP are ranked among the top ten in the Chinese industry in terms of the technical progress index, ranking third, ninth, and eighth, respectively. However, due to the low technical efficiency of OGE and MFP, their GTFP rankings are in the middle of the pack, at 18th and 17th, respectively. CMC's technical efficiency and technical progress index are both at the upper-middle level, with CMC and PCP sharing the seventh place in the GML index ranking among the Chinese industry. Among PI's five sub-industries, RPP ranks behind in terms of technical efficiency and technical progress index, with a GTFP ranking of 26th. It can be seen that the low technical efficiency of PI's sub-industries has severely restricted the improvement of GTFP. Thus, PI should focus on improving the technical efficiency of each industry and comprehensively enhancing the GTFP level of RPP.

PI and Sub-Industry Analysis

Tables 5 to 7 describe the green total factor productivity index, technical efficiency index, technical progress index, and averages of PI sub-industries.

Table 5 Evolution of GML index for PI sub-industries from 2002 to 2019

Year	OGE	PCP	CMC	MFP	RPP	Average value
2002	0.9475	0.9269	1.0047	1.0582	1.0099	0.9894
2003	1.0703	1.0407	1.0427	0.9449	0.9296	1.0056

2004	1.0384	1.0680	1.0709	1.0125	1.0217	1.0423
2005	1.0706	1.0000	0.9969	1.0042	1.0047	1.0153
2006	1.0355	1.0000	0.9970	1.0090	1.0037	1.0090
2007	0.9871	0.9929	1.0354	1.0102	1.0041	1.0059
2008	1.0964	1.0071	1.0397	0.9776	1.0054	1.0252
2009	0.8044	0.9550	0.9731	0.9746	0.9686	0.9351
2010	1.0573	1.0070	1.0520	1.0375	1.0097	1.0327
2011	1.0152	1.0399	1.0776	1.0207	1.0186	1.0344
2012	0.9731	0.9951	0.9985	0.9591	0.9814	0.9814
2013	1.0145	0.9822	1.0037	0.9874	0.9871	0.9950
2014	0.9647	0.9641	0.9975	0.9672	0.9981	0.9783
2015	0.8776	0.9210	0.9470	0.9805	0.9906	0.9433
2016	0.9433	1.0022	0.9856	0.9967	0.9987	0.9853
2017	1.0260	1.0764	0.9150	0.9819	0.9705	0.9940
2018	1.0299	1.0602	0.9350	0.9955	0.9602	0.9962
2019	0.9952	1.0076	0.9739	1.0316	1.0102	1.0037
Average value	0.9971	1.0026	1.0026	0.9972	0.9929	0.9985

Table 6 Evolution of GMLEC index for PI sub-industries from 2002 to 2019

Year	OGE	PCP	CMC	MFP	RPP	Average value
2002	0.9419	1.0000	1.0080	1.1115	1.0172	1.0157
2003	1.0889	1.0000	0.9643	0.8697	0.9732	0.9792
2004	1.0302	1.0000	1.0210	0.9828	1.0125	1.0093
2005	1.0886	1.0000	1.0337	1.0052	1.0162	1.0287
2006	1.0581	1.0000	1.0277	1.0253	1.0095	1.0241
2007	1.0848	1.0000	1.0453	1.0065	1.0175	1.0308
2008	1.0000	1.0000	1.0206	0.9621	1.0047	0.9975
2009	1.0000	1.0000	1.0215	0.9868	1.0356	1.0088
2010	1.0000	1.0000	1.0200	1.0642	1.0226	1.0214
2011	0.8498	1.0000	1.0635	1.0031	0.9888	0.9810
2012	0.9434	1.0000	1.0107	0.9545	0.9900	0.9797
2013	0.9794	1.0000	0.9717	0.9739	0.9846	0.9819
2014	0.9623	1.0000	1.0232	0.9959	1.0322	1.0027
2015	0.8510	1.0000	1.0058	0.9903	0.9932	0.9681
2016	0.9680	1.0000	0.9884	1.0338	1.0125	1.0005
2017	1.0250	1.0000	0.9688	0.9773	0.9451	0.9832
2018	1.0002	1.0000	0.9081	0.9283	0.9294	0.9532
2019	0.9856	1.0000	0.9569	1.0538	1.0040	1.0001
Average value	0.9921	1.0000	1.0033	0.9958	0.9993	0.9981

Table 7 Evolution of GMLTC index for PI sub-industries from 2002 to 2019

Year	OGE	PCP	CMC	MFP	RPP	Average value
2002	1.0059	0.9269	0.9967	0.9520	0.9928	0.9749
2003	0.9829	1.0407	1.0814	1.0864	0.9552	1.0293
2004	1.0080	1.0680	1.0489	1.0303	1.0091	1.0329
2005	0.9834	1.0000	0.9644	0.9990	0.9887	0.9871
2006	0.9786	1.0000	0.9702	0.9841	0.9943	0.9854
2007	0.9100	0.9929	0.9905	1.0037	0.9868	0.9768
2008	1.0964	1.0071	1.0187	1.0162	1.0007	1.0278
2009	0.8044	0.9550	0.9526	0.9876	0.9354	0.9270
2010	1.0573	1.0070	1.0313	0.9748	0.9874	1.0116
2011	1.1947	1.0399	1.0133	1.0175	1.0302	1.0591
2012	1.0314	0.9951	0.9879	1.0047	0.9913	1.0021
2013	1.0358	0.9822	1.0328	1.0139	1.0025	1.0134
2014	1.0024	0.9641	0.9749	0.9711	0.9670	0.9759
2015	1.0312	0.9210	0.9416	0.9900	0.9974	0.9762
2016	0.9745	1.0022	0.9972	0.9641	0.9864	0.9849
2017	1.0010	1.0764	0.9445	1.0047	1.0269	1.0107
2018	1.0297	1.0602	1.0296	1.0724	1.0332	1.0450
2019	1.0097	1.0076	1.0178	0.9789	1.0062	1.0040
Average value	1.0076	1.0026	0.9997	1.0029	0.9940	1.0013

Overall analysis of PI.

According to Figure 1, the green total factor productivity index (GML) of PI fluctuated around 1 during the period of 2002-2019, with the entire change trajectory resembling an elongated "M". During the observation period, the trend of technological progress was basically consistent with that of total factor productivity, and the change of PI's green total factor productivity mainly depended on technological progress. The technology efficiency index showed a downward trend overall during the observation period. There were two extremely low values of the green total factor productivity index in 2009 and 2015, respectively, which were 0.9351 and 0.9433. The annual average of the green total factor productivity index was 0.9985, indicating a decline in PI's green total factor productivity, with an average annual decrease of 0.15%. The annual average of the technology efficiency index was 0.9981, indicating a decline in technology efficiency. The technology progress index was 1.0013, indicating that technological progress or a high degree of technological innovation promoted the growth of green total factor productivity.

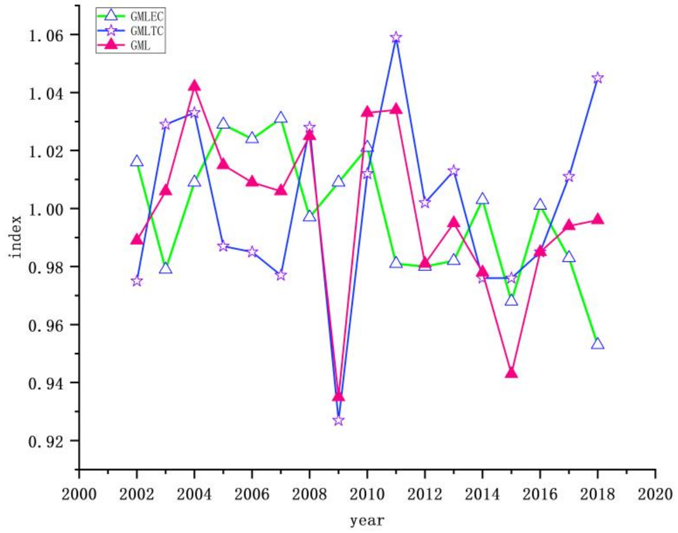

Figure 1 The annual scores and decomposition of green total factor productivity (GML) of PI from 2001 to 2019

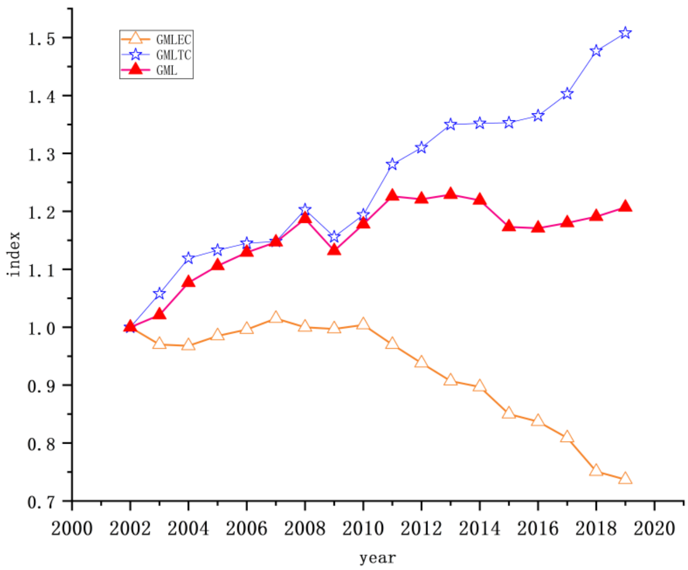

Figure 2. Cumulative index and decomposition of PI's green total factor productivity.

Assuming that the initial values of the productivity and decomposition indices in 2002 were 1, this paragraph tracks the changes in the cumulative green total factor productivity index, cumulative technical efficiency index, and cumulative technical progress index for PI. As shown in Figure 2, the cumulative green total factor productivity index and cumulative technical progress index exhibit a continuously increasing trend, both of which are above 1. The growth rate of the cumulative technical progress index is greater than that of the cumulative green total factor productivity index. Since 2002, the cumulative technical efficiency index has been consistently below 1 and shows a continuous decreasing trend, indicating the persistent deterioration of PI's cumulative technical efficiency. The main reason for the sustained increase in cumulative green productivity is that the cumulative technical progress index is always greater than the cumulative green productivity index.

The cumulative technical efficiency index always moves in the opposite direction to the trend of the cumulative green productivity index.Under the joint effect of the technical progress index and technical efficiency index, the deterioration of technical efficiency cannot completely affect the continuous growth of PI's green productivity.

Analysis of PI's Sub-Industries

Based on Table 5 and Figure 3, it can be observed that the green total factor productivity (GTFP) of PI sub-industries exhibits alternating positive and negative growth rates, indicating the unstable growth of GTFP across sub-industries. The average value of the GTFP index of sub-industries in PI, namely PCP, and CMC, is greater than 1, with a value of 1.0026 and an annual growth rate of 0.26%. In contrast, the remaining sub-industries have GTFP indices less than 1, with OGE at 0.9971, MFP at 0.9972, and the lowest being RPP at 0.9929.

Since the international financial crisis in 2008-2009, the energy-intensive petrochemical industry has been experiencing sustained low growth in total factor productivity (TFP). PI TFP exhibited a significant decline in 2008 and 2009 during the early stages of the financial crisis, followed by a recovery and then stagnation and decline after 2012. This is attributed to China's rapid introduction of a 4 trillion yuan economic stimulus package post-crisis, which revived many energy-intensive, polluting, and low-efficiency petrochemical enterprises. The economic growth during this period was more dependent on input factors. Due to excessive investment and inefficiencies, coupled with the typical lag effect of economic variables, these limitations gradually became apparent after 2011, leading to a decline in TFP. In 2015, the Chinese government launched the 13th Five-Year Plan, which aimed to reduce overcapacity, promote industry transformation and upgrading, advance structural adjustment, and carry out supply-side reforms, forming new growth drivers for the industry and resulting in the rise

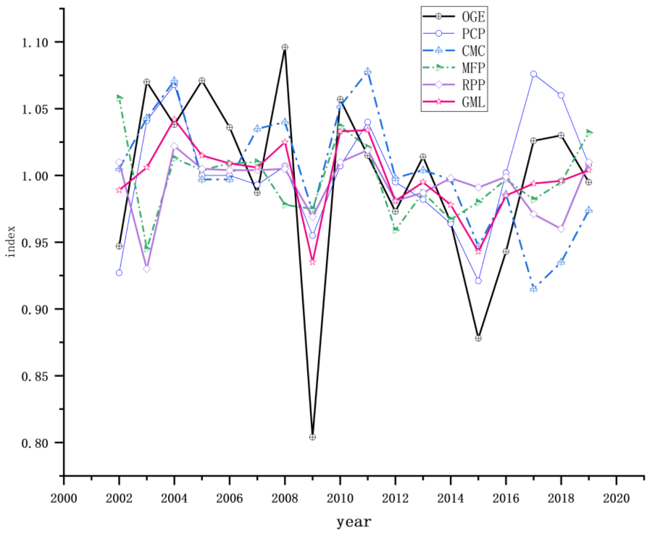

Figure 3 The trend of the GML index for PI's sub-industries

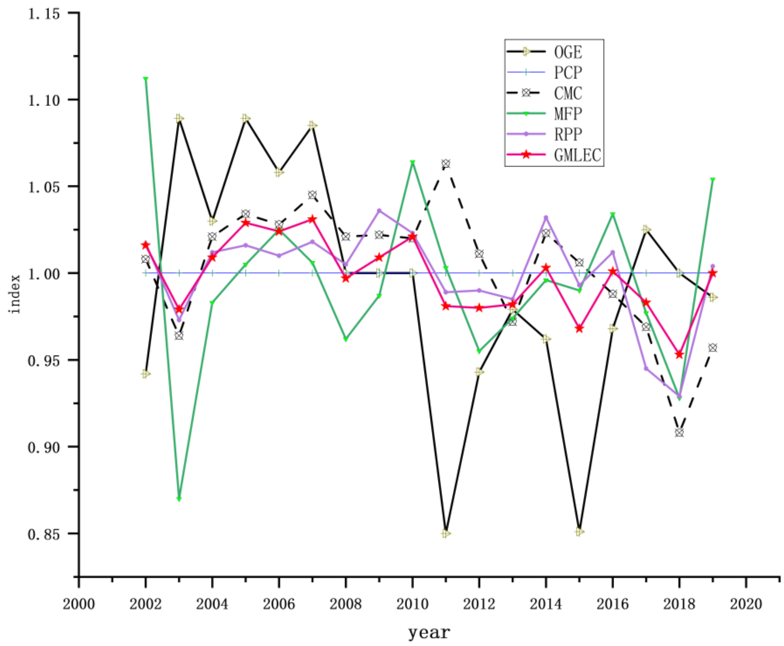

Figure 4 presents the trend of the GMLEC index for PI's sub-industries

Based on Table 6 and Figure 4, it can be observed that.In terms of PI's sub-industries technology efficiency index, PCP has an average index of 1.000, CMC has 1.0033, OGE has 0.9921, MFP has 0.9958, and RPP has 0.9993. Except for PCP, which maintained a constant technology efficiency index during the observation period, most of the OGE, CMC, and RPP subindustry's technology efficiency index was mostly greater than 1 in the first half of the observation period, indicating their proximity to the production frontier, thereby promoting green total factor productivity's growth and efficient production. However, the sub-industries experienced unstable fluctuations of around 1 in the latter half of the observation period. During the "Thirteenth Five-Year Plan" period, the technology efficiency index of each industry experienced a process of decline and growth, which was related to PI's active efforts to resolve overcapacity, promote industry transformation and upgrading, adjust the industrial structure, and promote productivity growth. The average value of PI's technology efficiency index is only 0.9981, indicating that the technical efficiency factor generally inhibits the growth of PI's green productivity.

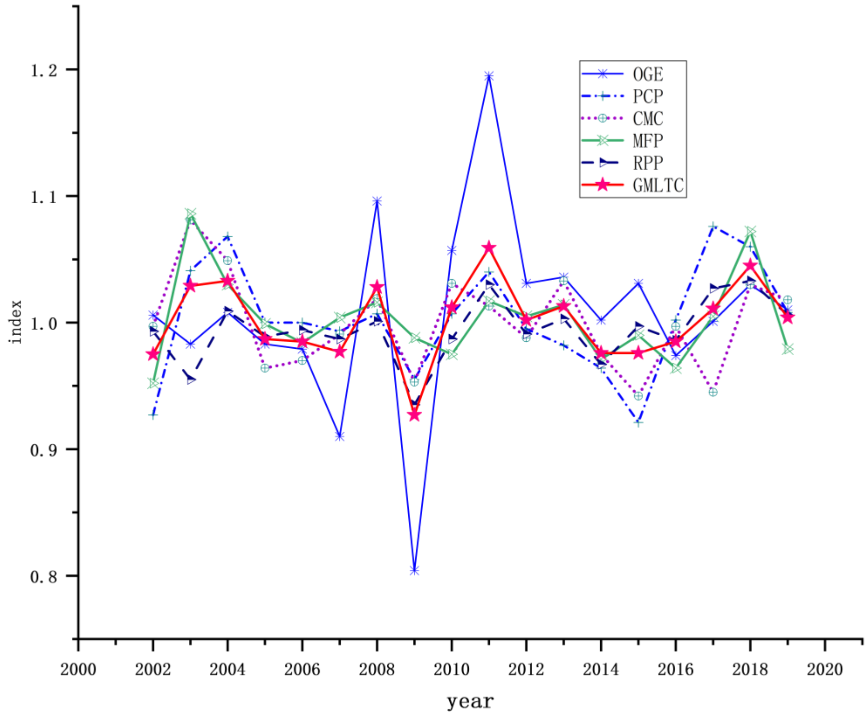

Figure 5 shows the trend of the GMLTC index for PI's sub-industries

Based on the results presented in Table 7 and Figure 5, it can be observed that the average annual technology progress indices for the OGE, PCP, and MFP sub-sectors of PI were greater than one, with growth rates of 0.76%, 0.26%, and 0.29%, respectively. This indicates that these sub-sectors are closer to the global production frontier and have made significant technological advancements or high-tech innovations, thereby promoting the growth of green total factor productivity. On the other hand, the CMC and RPP sub-sectors had technology progress indices of 0.9997 and 0.9940, respectively, indicating either a lack of technological innovation or a decline in technology. Throughout the observation period, the technology progress indices of each sub-sector fluctuated around one. During the 13th Five-Year Plan (2016-2020), the technology progress indices for PI's sub-sectors showed an increasing trend, with an average value of 1.0013, indicating that technology progress factors overall contributed to the growth of PI's green total factor productivity.

Table 8 describes the average and cumulative indices of PI's green productivity and its decomposition values. From 2001 to 2019, the green total factor productivity of PI's sub-sectors was 0.9985, with an average annual growth rate of -0.15%, indicating a decline in PI's sub-sector green total factor productivity, with a negative growth rate of 2.78% in cumulative indices. From the perspective of green total factor productivity decomposition factors, PI's technology efficiency index showed a negative growth rate of 0.19%, with a cumulative index of -3.4% negative growth. PI's technology progress index grew by 0.13%, with a cumulative index growth rate of 2.41%. It can be seen that technological progress factors are the main driving force behind the growth of PI's green total factor productivity. Among them, the OGE sub-sector had the highest annual growth rate and cumulative index growth rate for technology progress indices, at 0.76% and 13.73%, respectively. The RPP sub-sector had the lowest annual growth rate and cumulative index growth rate for technology progress indices, at -0.6% and -10.85%, respectively. The CMC sub-sector had the highest annual growth rate and cumulative index growth rate for technology efficiency indices, at 0.33% and 5.9%, respectively. The OGE sub-sector had the lowest annual growth rate and cumulative index growth rate for technology efficiency indices, at -0.79% and -14.26%, respectively. The PCP and CMC sub-sectors had the highest annual growth rate and cumulative index growth rate for green total factor productivity indices, at 0.26% and 4.6%, respectively. The RPP sub-sector had the lowest annual growth rate and cumulative index growth rate for green total factor productivity indices, at -0.71% and -12.7%, respectively.

Table 8: Average and Cumulative Indices of PI Green Productivity and Its Decomposition Values from 2002 to 2019

industry	Average index			Cumulative index		
	GML	**GMLEC**	**GMLTC**	**GML**	**GMLEC**	**GMLTC**
OGE	0.9971	0.9921	1.0076	0.9470	0.8574	1.1373
PCP	1.0026	1	1.0026	1.0461	1.000	1.0461
CMC	1.0026	1.0033	0.9997	1.0460	1.0590	0.9942
MFP	0.9972	0.9958	1.0029	0.9490	0.9251	1.0516
RPP	0.9929	0.9993	0.9940	0.8730	0.9887	0.8915
Petrochemical industry	0.9985	0.9981	1.0013	0.9722	0.9660	1.0241

VI. Analysis of Influencing Factors on Green Total Factor Productivity

Based on the above analysis, we construct an econometric model to further explore the internal mechanism of PI's green productivity growth and test the influencing factors of PI's green productivity and its decomposition variables

Variable Selection and Model Specification

Variable Selection

Based on careful consideration of internal and external factors and related characteristics of PI green development, and taking into account the development features of PI's sub-industries in the economy, energy, and carbon emissions. factors such as endowment structure, R&D investment, energy structure, and foreign direct investment were chosen as explanatory variables due to data availability. Green total factor productivity (GTFP), technical efficiency, and technological progress of PI sub-industries were selected as dependent variables, and a two-way fixed-effects model was adopted to examine the factors and degrees of influence on green total factor productivity Study the factors and extent of the impact on the green total factor productivity (GTFP) and its decomposition variables of PI sub-industries from 2001 to 2019.

KL represents endowment structure, R&D represents the research and development level, NYJG represents energy structure, and FDI represents a foreign direct investment. Control variables include industry concentration (CON) and energy utilization efficiency (NYLY).

Table 9 Variable Description

Variables	Names	Measurement	Symbols
Dependent Variables	Total Factor Productivity Index	Total Factor Productivity Index	GML
	Technical Efficiency Index	Technical Efficiency Index	GMLTC
	Technological Progress Index	Technological Progress Index	GMLEC

Independent Variable	Endowment Structure	Capital Stock to Employment Ratio	KL
	R & D Level	R & D Investment	RD
	Energy Structure	Coal Consumption as a Percentage of Energy	NYJG
	Foreign Direct Investment	The ratio of Foreign Capital Divided by Paid-in Capital	FDI
Control Variables	Industry Concentration	Number of Enterprises above Designated size	CON
	Energy Efficiency	The ratio of Energy Consumption to Total Industry Output	NYLY

Ratio of energy consumption to total industry output

Model Specification

To analyze the impact of various factors, the following empirical model is specified:

$$ln\,GML_{it} = \beta_0 + \beta_1\,ln\,R\&D_{it} + \beta_2\,ln\,KL_{it} + \beta_3\,ln\,NYJG_{it} + \beta_4\,ln\,FDI_{it} + \beta_5\ln CON_{it} + \beta_6\ln NYLY_{it} + u_t + \delta_i + \varepsilon_{it} \quad (5-1)$$

$$ln\,GMLTC_{it} = \gamma_0 + \gamma_1\,ln\,R\&D_{it} + \gamma_2\,ln\,KL_{it} + \gamma_3\,ln\,NYJG_{it} + \gamma_4\,ln\,FDI_{it} + \gamma_5\ln CON_{it} + \gamma_6\ln NYLY_{it} + u_t + \delta_i + \varepsilon_{it} \quad (5-2)$$

$$ln\,GMLEC_{it} = \alpha_0 + \alpha_1\,ln\,R\&D_{it} + \alpha_2\,ln\,KL_{it} + \alpha_3\,ln\,NYJG_{it} + \alpha_4\,ln\,FDI_{it} + \alpha_5\ln CON_{it} + \alpha_6\ln NYLY_{it} + u_t + \delta_i + \varepsilon_{it} \quad (5-3)$$

In the model, i and t represent industry and year, respectively. δ_i represents individual effects.$\mu_t$represents time fixed effects, and ε_{it} represents random disturbances.

VII. Empirical Results and Analysis

Descriptive Statistics of Variables

The specific descriptive statistics of each variable are shown in Table 10:

Table 10: Descriptive Statistics

Variables	Obs	Mean	Std. Dev.	Min	Max
GML	84	0.998	0.037	0.878	1.078
GMLEC	84	0.996	0.043	0.85	1.089
GMLTC	84	1.003	0.039	0.91	1.195
KL	84	44.8	36.977	7.107	163.412
RD	84	166.258	227.941	5.787	923.404
NYJG	84	0.148	0.099	0.013	0.371
FDI	84	0.058	0.042	0.001	0.196
CON	84	0.915	1.004	0.011	2.95
NYLY	84	2.014	1.104	0.672	5.498

Regression Results and Analysis

To make the data more stable, all variables are logarithmically transformed. Before estimation, the F-test and Hausman test were used, and the results showed that the parameters should be estimated using a fixed-effects model. The regression results are shown in Table 11:

Table 11: Econometric Regression Results

	(1)	(2)	(3)
Variables	lnYGML	lnYGMLTC	lnYGMLEC
lnKL	-0.164***	0.065	-0.227**
	(-5.07)	(1.49)	(-3.50)
lnRD	0.035***	-0.030	0.066**
	(5.62)	(-1.43)	(2.97)
lnNYJG	-0.030***	-0.017	-0.013
	(-4.63)	(-1.35)	(-2.04)
lnFDI	-0.008*	-0.023***	0.013**
	(-2.61)	(-4.88)	(3.51)
lnCON	-0.045*	0.110**	-0.155**
	(-2.22)	(2.84)	(-2.93)
lnNYLY	0.000	0.043*	-0.036
	(0.00)	(2.18)	(-1.02)
_cons	0.249**	-0.023	0.259*
	(3.02)	(-0.18)	(2.56)
Individual fixed effects	Yes	Yes	Yes
Time fixed effects	Yes	Yes	Yes
Observations	84	84	84
adj.R2	0.604	0.525	0.502

***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

Foreign investment (represented by the ratio of foreign capital used to paid-in capital) is used to replace the core explanatory variable of foreign direct investment (FDI) and tested for robustness.

From the perspective of the PI industry level, the empirical results of GTFP indicate that the endowment structure regression coefficient is negative, which suggests that the impact of endowment structure factors on GTFP at the PI sub-industry level is overall negative and significant. On the one hand, PI belongs to a high energy-consuming and labor-intensive industry, with weak capital deepening. However, labor-intensive industries often have a low level of technology, which hinders the development and application of green technologies in PI and further has a negative impact on the environment and resources. In addition, the capital accumulation of PI is often dominated by direct investment, which has promoted the rapid development of PI. However, the improvement of capital-labor during this stage is mainly driven by the extensive expansion of the PI scale. The extensive expansion of the PI scale has further led to environmental and ecological degradation. The regression results show that the R&D level factor has a positive and significant effect on GTFP at the PI industry level. R&D level, including technological innovation, directly restricts the process of PI's green transformation, especially the development and innovation of green environmental protection technologies. Although the existing R&D level of PI's sub-industries has promoted the improvement of PI's green productivity, overall, there is still great potential for the promotion and application of green environmental protection technologies in PI, which is also a breakthrough point for the future green development and low-carbon transformation of PI. The empirical evidence shows that the impact of energy structure on GTFP at the PI industry level is significantly negative. The fossil energy consumed in the production processes of various PI sub-industries is mainly coal, which not only consumes a large amount of non-renewable energy but also releases a large number of pollutants into the ecosystem, thereby having a negative impact on GTFP in the PI industry level. The impact of foreign direct investment on GTFP at the PI industry level is significantly negative at the 0.1 level, which means that the increase in foreign direct investment has lowered the level of PI's GTFP, and the "pollution haven hypothesis" has been verified.

Based on the empirical results of the technological efficiency at the industry level of PI, the endowment structure factor is significantly negatively correlated with technological efficiency, indicating that an increase in capital deepening does not promote technological efficiency improvement, possibly due to the earlier period's extensive capital accumulation. The R&D level factor is significantly positively correlated with technological efficiency, indicating that the improvement of the R&D level is beneficial to the improvement of technological efficiency in various sub-industries of PI, and the high or low level of R&D directly constrains the process of technological efficiency improvement. The energy structure factor shows a negative correlation with technological efficiency, but it is not significant, indicating that the increase in coal energy consumption does not contribute to the improvement of technological efficiency. On the one hand, the high carbon emission coefficient of coal itself in fossil energy will bring more pollution and management problems with an increase in coal consumption. On the other hand, it may be related to the low coal utilization rate of PI's sub-industries. The factor of foreign direct investment is significantly positively correlated with technological efficiency, and the addition of foreign capital can bring advanced management processes and working methods, thereby improving technological efficiency.

The empirical results of technological progress at the PI industry level indicate that endowment structure factors are positively correlated with industry technological progress, but not significantly so. This suggests that the increase in the capital-labor ratio has triggered a transformation in production methods, accelerating technological progress in the industry. R&D level factors are negatively correlated with industry technological progress, but not significantly so. Bi Kexin argues that innovation in R&D investment positively drives the development of clean production technology in companies [48].However, the fact is that R&D investment may have a dual impact on green technology progress. On the one hand, an overall increase in R&D investment leads to a corresponding increase in green R&D investment by companies, thereby promoting green technological progress. On the other hand, excessive R&D investment may not necessarily have a green bias and may enter non-green technology R&D areas, suppressing the green development of the industry and hindering green technological progress. Energy structure factors are negatively correlated with industry technological progress, but not significantly so. This indicates that the increase in coal consumption exacerbates the industry's technological regression, and there is a need to control the coal consumption of the PI's sub-industries and improve energy utilization efficiency. Foreign direct investment factors are significantly negatively correlated with industry technological progress. Foreign investment is becoming a channel for developed countries to transfer pollution emissions to developing countries. Investment capital seeks economic benefits and does not pay much attention to the development of green technology, hindering the progress of green technology.

VIII. Recommendations for green development.

Based on empirical analysis of the GTFP and its influencing factors in the PI industry, this study proposes suggestions for green development in the PI sector. Given PI's significant role in China's industrial sector, it is important to continue improving technical efficiency and increasing technological progress to promote PI's green total factor productivity growth, facilitate its green development, and promote low-carbon transformation. To this end, promoting digital and intelligent technology research and development is crucial to move PI away from labor-intensive industries. By establishing a carbon trading market that rewards good behavior and punishes bad, incentives can be created to stimulate PI's proactive participation in green production. Increasing investment in green research and development in the petrochemical industry will also promote the creation of green technology. Furthermore, developing and utilizing new clean energy technologies and gradually reducing the proportion of fossil fuels can optimize PI's energy structure and accelerate energy transformation. Introducing foreign or private capital under the premise of ensuring the green development of petrochemical projects and actively monitoring investment quality can contribute to improving PI's green productivity. Finally, it is essential to further improve the PI regulatory framework, establish industry green evaluation standards, adjust industry structure, and facilitate the green transformation to achieve sustainable green development.

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