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Does Technological Innovation Promote Haze Pollution Control? New Evidence Based on Panel Threshold Model and Spatial Econometric Model

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Since the reform and opening up, China's rapid economic growth mainly depends on the industrial development mode of "high energy consumption and high pollution," which has caused serious haze pollution. In order to achieve the goal of haze control and sustainable development, we need to give full play to the role of technological innovation. Empirical analysis of the haze control effect of technological innovation has theoretical significance and practical value. Based on the panel data of 30 provinces in China from 2005 to 2018 and the PM2.5 concentration data published by the atmospheric composition analysis group of Dalhousie University, this study selects R&D personnel input and technology market turnover to represent the level of technological innovation and uses the panel data model, threshold effect model, and spatial Durbin model to empirically analyze the impact of technological innovation on haze pollution control. The empirical results show that 1) technological innovation can significantly reduce the PM2.5 concentration of the province, showing a positive haze control effect; 2) technological innovation indicates a negative indirect effect on PM2.5 concentration, confirming the "technology spillover effect," that is, technological innovation also has a haze control effect on the surrounding provinces; 3) with the increase in the province's economic aggregate, the haze control effect of technological innovation shows a trend of "high low high," and the role of technological innovation is the lowest in the stage of economic transformation; and 4) from the perspective of regional differentiation, the haze control effect of technological innovation is the largest in the central region, and the smallest in the western region. Technological innovation indicates a positive haze control effect on all regions at all stages of economic development. This study provides policy suggestions for the government and enterprises to use innovation for cleaner production and sustainable development.

Keywords: technological innovation, haze pollution, technology spillover effect, panel threshold model, China

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INTRODUCTION

Industrial development is the main driving force of China's economic growth in recent years. China's total industrial output value increased from 423.7 billion yuan (unit/RMB) in 1978 to 30,516 billion yuan in 2018; the industrial scale increased more than 70 times. However, China's industrial development mainly depends on high energy consumption and rough expansion mode, forming the characteristics of "high energy consumption and high pollution" (Han et al., 2019). Particularly, as the main energy to support the industry, the proportion of coal consumption has remained high for a long time, coupled with the low efficiency of energy utilization, resulting in serious air pollution. As an important factor restricting the sustainable development of economy and society, PM2.5 has a significant negative impact on residents' health, stable economic growth, industrial transformation, and ecological environment. In addition, the city's density of eastern China is high, and the air flow between cities is frequent. The air pollution of a city will produce a spillover effect on the surrounding cities through the air flow, thus forming a "pollution haven" in a certain area (Ahmad et al., 2021). In June 2013, the state council issued "ten measures for the prevention and control of air pollution," which clearly put forward the goals of reducing PM2.5 concentration in key areas and strictly preventing severe pollution weather. In recent years, China's PM2.5 governance has shown a good trend. However, many scholars hold that China has not completely got rid of the ecological damage caused by the rough development model (Zhou et al., 2021). Haze pollution control still has considerable space in sustainable development. Therefore, it is of great theoretical significance and practical value to analyze the economic means of haze control.

Technological innovation is an important driving force to promote green and sustainable development (Altıntaş and Kassouri., 2020). In 2012, the 18th National People's Congress of the Communist Party of China clearly put forward that scientific and technological innovation should be the core element to improve social productivity. The effect of technological innovation on green development is mainly realized by the following two ways: First, from the micro perspective, technological innovation will optimize the existing energy combustion technology and improve energy efficiency and reduce energy intensity. According to the data released by the World Bank, China's energy consumption per unit of GDP decreased from 843 (G standard oil/US dollar) in 1980 to 166 (G standard oil/US dollar) in 2015. Second, from a macro-perspective, technological innovation helps to optimize the industrial structure. Promote the transformation of industrial structure from heavy industry to high-tech industry and high-end manufacturing industry. According to China Statistical Yearbook, the technology transaction volume of 30 provinces in mainland China has increased rapidly from 155.1 billion (yuan/RMB) in 2005 to 1, 713.7 billion (yuan/RMB) in 2018, which is much higher than GDP and other major economic indicators. In addition, cleaner production technology will also show a significant spatial spillover effect. Advanced production technology in central cities will improve the level of science and technology in surrounding areas through talent flow and technology trade. Therefore, it is of great significance to analyze the role of technological innovation in haze pollution control.

The rest of this article is arranged as follows: the second section is literature review; the third section describes the temporal and spatial characteristics of PM2.5 concentration in China; the fourth section is the model and variable selection of this study; the fifth section is the empirical results; the sixth section further analyzes the haze control effect of technological innovation; and the seventh section is the conclusion and policy recommendations.

LITERATURE REVIEW

Haze pollution is an important factor restricting regional sustainable development. In a broad sense, haze pollution includes PM2.5, PM10, NOx, and other air pollutants. Zhang et al. (2019)'s research points out that PM2.5 is the main source of air pollution in China at this stage. Therefore, it is of great value to analyze the driving factors of mitigating PM2.5. The root cause of haze pollution in China is the defects of energy structure and industrial structure in the rapid economic growth (Zhang et al., 2020) and life expectancy (Song et al., 2019), which affects residents' choice of work and living city and forms the phenomenon of "voting with feet" (Douglas and Wall, 1993). In addition, haze pollution in turn may have a restrictive effect on green economic development, affecting the development of the tertiary industry and high-tech industry (Feng et al., 2021a). Among the spatial distribution characteristics of haze pollution, existing studies have widely proved that haze pollution has spatial correlation among provinces or cities (Du et al., 2018). The air quality in this region not only depends on the technological innovation and sustainable development of the city but also is significantly affected by the surrounding areas, namely, "pollution paradise" or "pollution haven" (Lin and Xu, 2019). Most studies have empirically proved the spatial agglomeration characteristics of "high" or "low" pollution in China: Yan et al. (2018) analyzed the temporal and spatial characteristics of PM2.5 concentration in a year by using the monthly data of 13 cities in the "Beijing–Tianjin–Hebei" region. Chen et al. (2019) proved the spatial spillover effect of haze pollution based on the quarterly PM2.5 data of provincial ground monitoring; the conclusion shows that haze concentration in the eastern region was the most significant. The research of Shan et al. (2020) shows that there are several significant "high pollution" concentration areas in China's coastal areas, among which the haze pollution in the "Beijing–Tianjin–Hebei" region and the Yangtze River Delta is the most prominent. Wang et al. (2017) used the panel data of 5,674 industrial enterprises in the Anhui Province to prove that industrial pollution emissions also have a spatial spillover effect among enterprises, and geographically adjacent enterprises will show similar pollution characteristics. As for the research of regional haze pollution, whether the data can accurately reflect the real pollution level is important. The existing PM2.5 data mainly come from the following sources: first, the monitoring data provided by ground monitoring stations; second, the PM2.5 concentration data provided by satellite monitoring. Because the ground monitoring data will be affected by the air quality around the monitoring point, there is a problem that it cannot reflect the overall regional haze pollution. Columbia University and Dalhousie University Atmospheric Composition Analysis Group used NASA satellites to monitor PM2.5 concentrations in major regions. Satellite monitoring data paid more attention to the actual performance of regional haze pollution and focused on the pollution results caused by economic activities, which is more representative. To sum up, this study will use the PM2.5 concentration data published by Dalhousie University Atmospheric Composition Analysis Group to empirically analyze the spatial agglomeration characteristics and spatial spillover effects of haze pollution in China.

Industrial structure, economic growth, energy consumption, foreign direct investment, and other factors will affect PM2.5 concentration. Fang and Yu (2021) hold that industrial development is the main driving force of PM2.5 emission and concludes that energy intensity is an important factor to promote economic growth and pollution decoupling. Xie and Sun (2020) used the generalized panel smooth transition regression (GPSTR) model to prove that foreign direct investment (FDI) can lead sustainable development and haze pollution control, but there is a "S-type" relationship between FDI and PM2.5. With the accumulation of FDI, its pollution control effect will gradually weaken. In addition, there may be a non-linear relationship between economic growth and haze pollution, namely, the "Environmental Kuznets Curve" (Ding et al., 2019). In the early stage of economic development, economic growth has led to serious haze pollution; with the technological update and people's demand for clean environment, economic growth relies more on technology oriented clean production technology and high-tech industries, and ultimately economic growth will reduce haze pollution. The research of He and Lin (2019) shows that only some provinces in eastern China have crossed the turning point of EKC, while most cities in central and western China are still on the left side of EKC. Bilgili et al. (2021) employed a panel quantile regression model to verify the environmental Kuznets Curve. Dietz and Rosa (1994) improved the IPAT model, namely, the STIRPAT model. The model proposes that population (P), affluence (A), and technology (T) are the three core factors affecting pollution. As an uncompetitive commodity, technology can play a greater role than the change of population and affluence. Environmental-friendly technology can promote the cleaner production of the whole industry through technology trade, industrial transfer and other ways. Therefore, it is of theoretical significance and practical value to analyze the haze control effect of technology. The existing research has made a guiding research in the related fields: Wu et al. (2020) took the "Beijing–Tianjin–Hebei" region as sample and employed the factor analysis method to evaluate the impact of economic factors and environmental factors on PM2.5 concentration, in which the role of R&D ranked first in all cities. Zhu et al. (2020) analyzed the emission reduction effect of renewable energy technology, and concluded that it significantly reduced the emissions of NO_X and PM10 but had no significant impact on the emissions of SO_2. Based on the panel data of 30 provinces in China from 2005 to 2016, Lou et al. (2021) empirically analyzed the spatial spillover effect of high-tech industry by using the spatial autoregressive model, spatial error model, and spatial Durbin model, that is, high-tech industry can not only significantly reduce SO_2 pollution in the province but also contribute to the sustainable development of surrounding provinces. In addition, Kassouri et al. (2021a) explored the vulnerability of clean energy and high-tech stock prices to oil shocks. Because different regions are in different stages of economic development, the haze control effect of technological innovation may be different. However, the existing studies lack discussion on this issue; this study will further explore this issue through the threshold effect model.

To sum up, the possible contributions of this study are as follows: 1) PM2.5 concentration data published by Dalhousie University Atmospheric Composition Analysis Group are used in this study, which pays more attention to the actual pollution results caused by economic activities, provides new empirical evidence for the research of haze pollution control; 2) the haze pollution control effect of technological innovation is analyzed through the panel data model, and the spatial Durbin model is used. This study analyzes the spatial agglomeration characteristics of haze pollution and the spatial spillover effect of technological innovation; 3) furthermore, through the threshold regression model, this study empirically analyzes whether there is a non-linear relationship between technological innovation and PM2.5 concentration with economic growth.

TEMPORAL AND SPATIAL CHARACTERISTICS OF PM2.5

The PM2.5 concentration data used in this study are from the atmospheric composition analysis group of Dalhousie University in Canada. The calculation method is based on the atmospheric concentration data published by NASA and the data from ground monitoring stations. According to the published PM2.5 concentration grid data, it is parsed into the corresponding data of each province by Arcgis10.0 software. The higher the PM2.5 concentration means more serious the haze pollution.

Figure 1 depicts the mean PM2.5 concentrations and the differences between eastern, central, and western regions of 30 sample provinces from 2005 to 2018. From the overall trend, the PM2.5 concentration curve showed an "inverted U shape" and reached the peak in 2011. During 2005–2011, PM2.5 concentration showed a zigzag increase, which may be related to the rapid growth of China's economy and the urbanization rate. According to China Statistical Yearbook, during 2005–2010, China's GDP increased from 18.49 trillion yuan to 31.46 trillion yuan, and the urbanization rate increased from 44.99 to 49.95%. Since 2013, the PM2.5 concentration has been decreasing rapidly. The average PM2.5 concentration of 30 provinces has decreased from 41.09 in 2013 to 28.63 in 2018. This is related to the government's powerful means of environmental regulation since the 12th Five Year Plan. The 12th Five Year Plan of national environmental protection clearly puts forward the requirements of establishing PM2.5 monitoring mechanism and effectively controlling compound air pollution in the Beijing–Tianjin–Hebei region, Yangtze River Delta, and Pearl River Delta. PM2.5 has gradually become one of the standards to measure government performance. From the regional differences of PM2.5 concentration, the eastern and central regions are always higher than the western regions, which may be related to economic and geographical factors. First, the eastern and

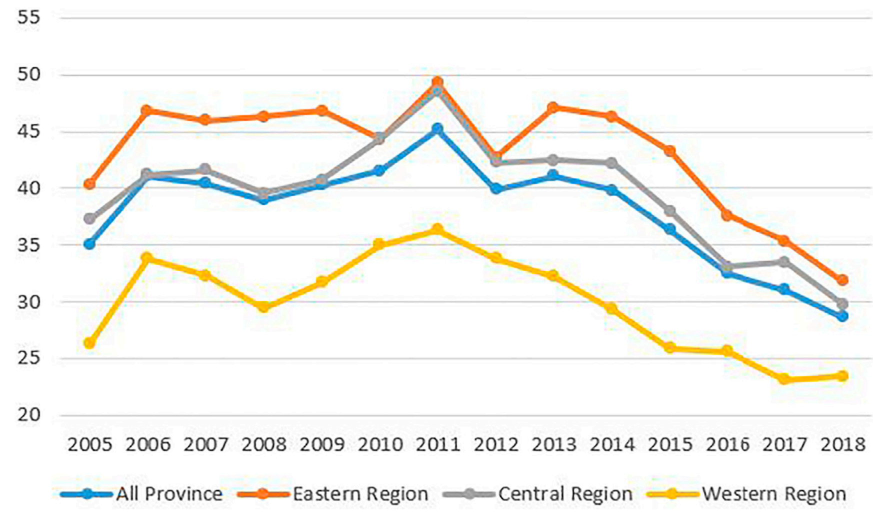

FIGURE 1 | Temporal variation of PM2.5 pollution from 2005 to 2018.

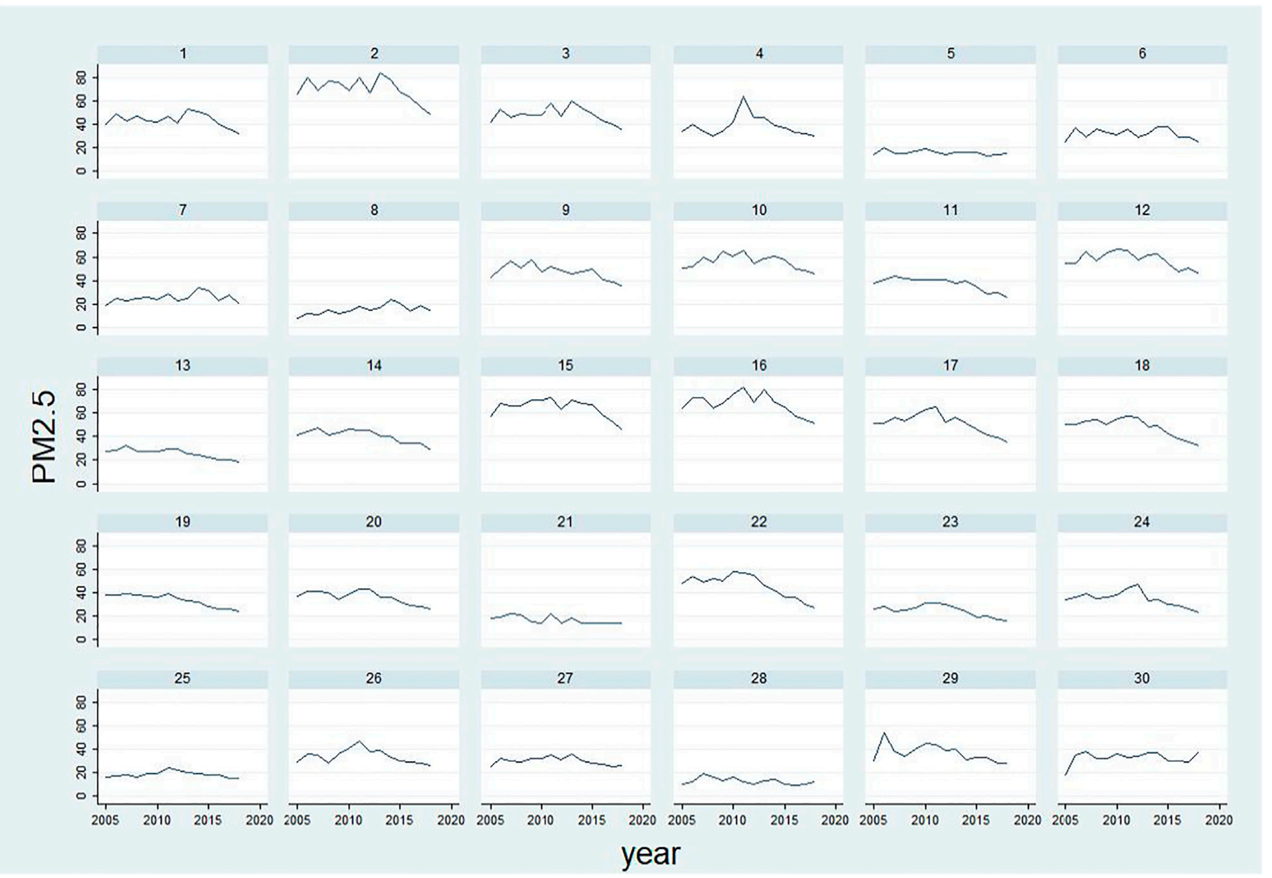

FIGURE 2 | Time trend of PM2.5 in 30 provinces from 2005 to 2018.

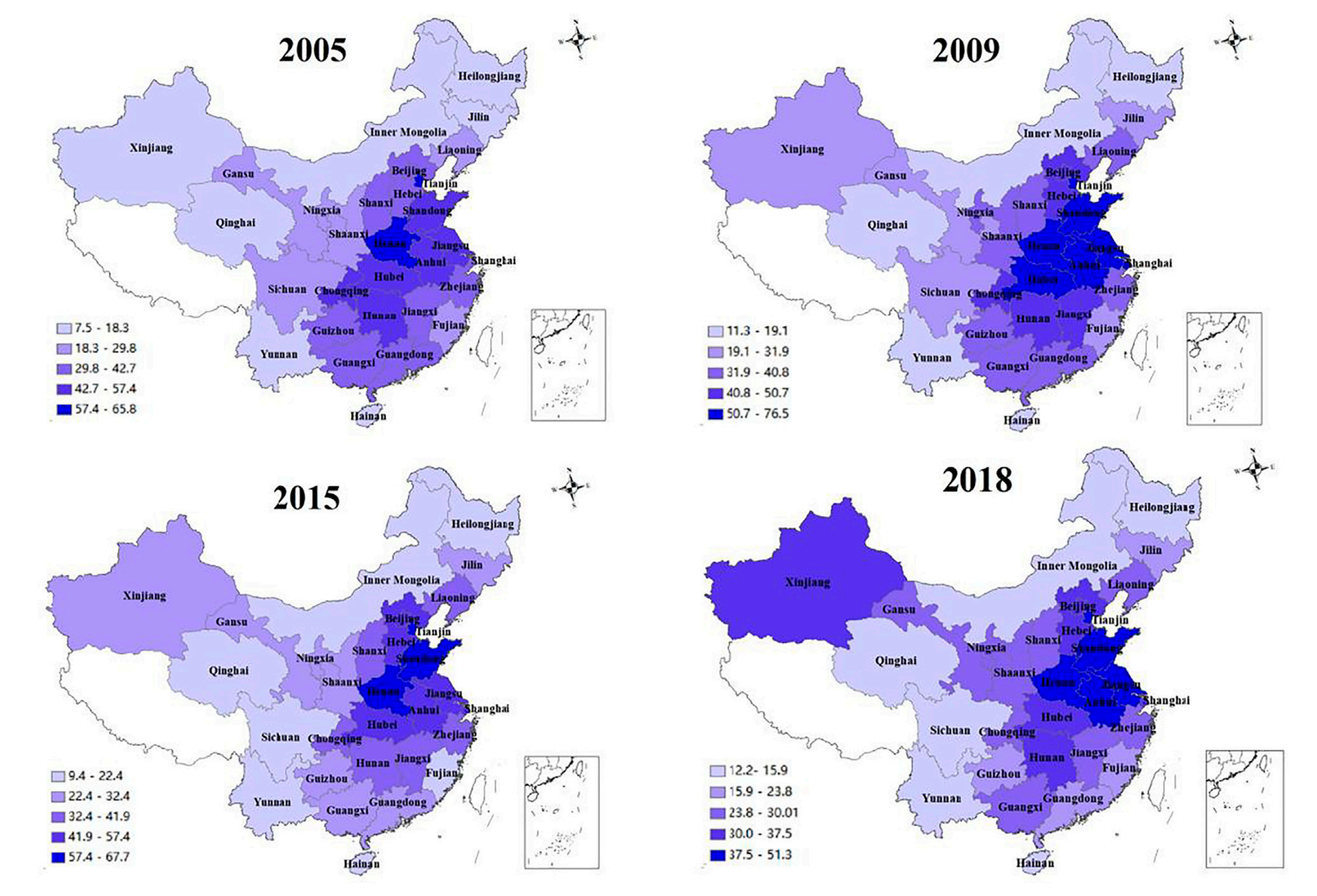

FIGURE 3 | Spatial distribution of PM2.5.

central regions have more developed economy, higher urbanization level, higher population density, and higher emissions of air pollutants from economic activities and social life. In the western region, except for a few core cities (such as Chengdu and Xi'an), most cities have low economic vitality. Second, from the analysis of geographical factors, the central and eastern regions are small and flat, while the western regions are vast and most of the land is plateau or desert with less human activities. Therefore, the concentration of PM2.5 in the western region is lower than that in the central and eastern regions.

Figure 2 depicts the change of PM2.5 concentration in each province from 2005 to 2018. We found that except for a few provinces with low PM2.5 concentration, PM2.5 concentration in most provinces showed an "inverted U-shaped" or continuous decreasing characteristics. This means that the results of haze control in China are the result of the joint efforts of all provinces, and the PM2.5 concentration of each province shows different degrees of reduction in the sample period.

Figure 3 depicts the spatial distribution characteristics of PM2.5 concentration in each province in 2005, 2009, 2015, and 2018. First, similar to the conclusion in **Figure 1**, PM2.5 concentration shows a "ladder" feature of gradual decline from east to west, that is, the haze pollution in eastern coastal areas and central areas is more serious than that in western areas. Second, in the spatial agglomeration characteristics, haze pollution shows a significant "high-high" or "low-low" agglomeration characteristics. The provinces with "Henan-Shandong-Jiangsu-Anhui" as the center showed higher PM2.5 concentration at all stages, forming a "pollution paradise." This reminds that the government not only need to improve its own green development level in haze pollution control but also need the "joint prevention and control" and joint cooperation among provinces. When all provinces are committed to haze pollution control, it will produce "1 + 1 > 2" effect. In addition, "Heilongjiang-Jilin-Liaoning-Inner Mongolia" and "Qinghai-Sichuan-Yunnan" showed a "low-low" concentration of PM2.5.

METHOD AND DATA

Econometric Model

In order to empirically test the haze pollution control effect of technological innovation, this study uses the panel data of 30 provinces in China from 2005 to 2018 for an empirical analysis. According to Zhong et al. (2021), we should first use mixed OLS regression, random effect model, and fixed effect model to get the basic results, and then use the threshold effect model and spatial econometric model for further analysis. Mixed OLS regression is a basic econometric model widely used in panel data. Its basic assumption is that there is no individual effect:

$$PM_{it} = \alpha + \beta_1 \ln rd_{it} + \beta_2 \ln tech_{it} + \delta X_{it} + \varepsilon_{it}. \quad (1)$$

PM represents the explained variable; lnrd and lntech represent the level of technological innovation; and β_1 β_2 are the most concerned values. It shows the haze control effect of technological innovation; X represents the control variable and is the coefficient set of each control variable; i and t represent the sample individual and period, respectively; and z is the individual effect that does not change with time and represents the disturbance term. However, because the mixed regression thinks that the regression equation of each individual is the same, that is, there is no heterogeneity in the situation of each province, which may be inconsistent with the reality. In fact, due to the differences in the economic level and social characteristics among provinces in China, there may be individual effects, which may exist in the form of fixed effects and random effects. The expression of the random effect model and fixed effect model is as follows:

$$PM_{it} = \alpha + \beta_1 \ln rd_{it} + \beta_2 \ln tech_{it} + \delta X_{it} + u_i + \varepsilon_{it}. \quad (2)$$

The meaning of each variable is the same as that of mixed regression model, but we assumed that u_i is not related to explanatory variable $\{X_{it}\}$, that is, the characteristics of the individual non-observable are independent of explanatory variables, but the fixed effect model considers that u_i is related to one or more explanatory variables. The two-way fixed effect model is as follows:

$$PM_{it} = \alpha + \beta_1 \ln rd_{it} + \beta_2 \ln tech_{it} + \delta X_{it} + u_i + \gamma_t + \varepsilon_{it}. \quad (3)$$

The expressions and letters of **Eqs 2**, **3** have the same meaning; γ_t represents time fixed characteristics. In order to test whether there are individual and time effects and whether individual effects are related to explanatory variables, we will introduce the F test, LM test, Hausman test, and significance test of year dummy variables to select the optimal model from the aforementioned models.

The First Law of Geography states that no city is isolated (Tobler 1970). Existing studies have pointed out that the spatial econometric model can avoid ignoring the spatial correlation among cities (Elhorst, 2003; Getis 2007; Anselin 2010). Haze pollution is not only affected by the variables of the local province but also may be affected by the "spillover effect" and "siphon effect" of the surrounding provinces. Therefore, we employed the spatial econometrics model to investigate the spatial correlation of haze pollution and its spillover effect. The most widely used and relatively mature spatial econometric models are the spatial lag model (SLM), spatial error model (SEM), and spatial Durbin model (SDM). The SLM only considers the spatial correlation of the interpreted variable, while the explanatory variables only affect the interpreted variable in the city but no spatial spillover effect (Ma et al., 2016; Wang et al., 2020). SEM is considered a reasonable model when the error term has spatial correlation (Haining 1978; Casetti 1986; Wang et al., 2020). The SDM places both the interpreted and the explanatory variables into the spatial correlation analysis. The model urges that multiple variables have spatial effects on the surrounding areas, and multiple factors contribute to the variation of the interpreted variables (Ouedraogo 2016; Lv et al., 2019). The SLM is set as follows:

$$PM_{it} = \rho \sum W^* PM_{it} + \theta X_{it} + \varepsilon_{it}. \quad (4)$$

In **Eq. 4**, w represents the spatial weight matrix established in this study; ρ, spatial autoregressive coefficient of PM2.5, is the most concerned numerical value in this equation; θ represents the explanatory variable parameter to be estimated; and ε_{it} represents the error term. SEM is set as follows:

$$\begin{cases} PM_{it} = \theta X_{it} + \varepsilon_{it} \\ \varepsilon_{it} = \lambda W * \varepsilon_{it} + \upsilon_{it} \end{cases}. \quad (5)$$

In Eq. 11, the spatial correlation of error terms is the main factor different from other models. The meaning of each variable is the same as **Eq. 4**. Then, SDM is set as follows:

$$PM_{it} = \rho \sum W^* PM_{it} + \gamma W^* X_{it} + \theta X_{it} + \varepsilon_{it}. \quad (6)$$

The meaning of each variable is the same as Eq. 11. The difference is that the SDM contains the spatial lag term of explanatory variables, which is expressed by γ. It will analyze the spatial spillover effect of the explanatory variables. Elhorst (2014) proposed the likelihood ratio (LR) test method for SLM, SEM, and SDM models, the test can identify whether the SDM could be simply reduced to the SEM or SLM (Elhorst 2014).

Variables and Data Sources

Explained variable. At present, the main source of haze pollution of China is PM2.5, so PM2.5 concentration is an important variable to measure haze pollution. Referring to the research of Zhang et al. (2019) and Zhao et al. (2020), this study uses the annual average PM2.5 concentration of each province to measure the haze pollution level. PM2.5 concentration data are taken from the atmospheric composition analysis group of Dalhousie University in Canada, and its calculation method is integrated from the atmospheric concentration data published by NASA and the data of ground monitoring station. According to the published PM2.5 concentration grid data, it is parsed into the corresponding data of each province through ArcGIS 10.0 software. The higher the PM2.5 concentration value, the more serious the haze pollution in the region. In addition, scholars Zhou J. et al. (2021) and Cheng and Zhu (2021) also used these data for research, pointed out that using these data can solve the difficulty of accurately measuring PM2.5 concentration in a certain area using surface detection data based on point source data. It can be seen that these are scientific and reliable data, which are in line with the haze trend published by the Ministry of Ecology and Environment of China (Zhang et al., 2019).

Explanatory variables. 1) Technological innovation. Technological innovation is the main driving force of sustainable development (Wang and Yang, 2021). The existing research in the selection of technological innovation indicators can be roughly divided into the following three categories: one is the use of innovation input indicators, such as government science and technology expenditure and education expenditure, enterprise R&D expenditure, and so on (Lou et al., 2021). The second is to use innovation output indicators, such as the number of patents granted, and new product sales (Cai et al., 2020; Feng et al., 2021b). The third is to calculate the efficiency of technological innovation by means of efficiency measurement (Chen et al., 2021). The number of green invention patent (*lnpatent*) is employed in this study to represents the technology innovation of provinces in consideration of the researches of Liu et al. (2021), Cho and Sohn (2018) and Wang et al. (2019). Compared with the method of measuring innovation ability by input factors, the number of green patent applications can accurately reflect the final results of provinces in green innovation activities and is closer to the green technologies actually available to enterprises and governments in the production process. The data sources of green patent applications are as follows: firstly, collect the data of patent applications in 30 provinces from 2005 to 2018 published by China National Intellectual Property Administration. Second, with reference to the seven major green patents (including alternative energy production, transportation, energy conservation and emission reduction, waste management, agriculture and forestry, administrative supervision or design, and nuclear power generation) and more than 200 minor items listed in the IPC Green Inventory launched by the World Intellectual Property Organization in 2010, combined with the collected data on the number of patent applications in China, select the number of patents in line with the international green patent classification list. Furthermore, according to China's patent system, green patents can be divided into green invention patent and green utility model patent. The green invention patent requires the patent to prominent substantive characteristics and significant progress, while the green utility model invention only needs marginal improvement in one aspect of the product or process.

Control variables. 1) Industrial development (*lngdp*). Industry is the main pillar of China's economic development since the reform and opening up. The industrial expansion mode of "high energy consumption and high pollution" has caused serious environmental consequences. In addition, the environmental Kuznets curve shows that when the industrial development crosses the inflection point, enterprises tend to cleaner production, and there is a negative correlation between industrial development and pollution. The existing studies in China show that only the provinces and cities in the eastern coastal areas of China may have crossed the turning point of EKC, while the central and western regions are still in the stage of "high pollution caused by industrial development." This study selects the GDP of the second industry (*lngdp*) to represent the level of industrial development. 2) Investment in industrial pollution control (*lnregulation*). In the process of China's industrialization, the government will also increase investment in environmental governance to promote sustainable development. In this study, investment in industrial pollution control (*lnregulation*) is selected to represent government's investment level in pollution control. 3) Energy intensity. Energy consumption per unit GDP (*energyten*) is selected to represent energy intensity. The lower the power consumption per unit GDP represents the less energy is needed for economic growth. On the one hand, technological innovation makes more full use of fossil energy and improves the production capacity of unit energy; on the other hand, the optimization of industrial structure makes economic growth gradually change from "energy driven" to "high-tech industry and tertiary industry driven," and economic growth relies more on low-energy industries. 4) Fiscal expenditure (*fiscal*). The impact of fiscal expenditure on haze governance is reflected in many aspects. First, the expenditure on science and technology and education in the financial expenditure will directly improve the level of science and technology and human capital and continuously inject power into the development of green economy. Second, financial expenditure can improve the transportation infrastructure, standardize the market, and carry out macro-control. This will help to eliminate the negative externalities of enterprises and improve the management ability. In this study, fiscal expenditure per capita (*fiscal*) is selected to represent the level of fiscal expenditure. 5) Government (*policy*). The impact of government policies on haze pollution is reflected in the impact of the government on enterprises through environmental regulation means or laws and regulations. The policy intensity may affect the location, cleaner production and other behaviors of enterprises. This study selects the occurrence times of words related to haze pollution (including PM2.5, PM10, air, emission reduction, pollution, and energy consumption) in the government work report to represent the intensity of environmental protection policy. The government work report is a summary of the government's achievements in the past year. Therefore, the number of relevant words in the report has a significant positive correlation with the government's policy intensity in environmental governance.

TABLE 1 | Statistical description of variables.

	Obs	Mean	Std.Dev	Min	Max
lnpm	420	3.5310	0.4836	2.0736	4.4261
lnpatent	420	5.1416	1.6761	0	8.7982
lngdp	420	8.5860	1.0228	5.3939	10.6274
lnregulation	420	11.8220	0.9775	8.1782	14.1637
lnenergyten	420	1.5843	1.1190	0.5518	6.4900
lnfiscal	420	0.8903	0.6618	0.1165	4.4579
lnpolicy	420	3.5407	0.4398	2.1972	4.6540

Data sources. PM2.5 concentration data are from the public data released by the atmospheric composition analysis group of Dalhousie University. The data of explanatory variables and control variables are from China Statistical Yearbook and China High-tech Industry Statistical Yearbook. **Table 1** reports descriptive statistics for each variable; the results of multicollinearity test are reported in **Supplementary Table S1**.

TABLE 2 | Estimation results of panel data models.

	Model-1	Model-2	Model-3	Model-4	Model-5
	(OLS)	(RE)	(FE)	(Two-way FE)	(Two-way FE)
lnpatent	0.088***	−0.090***	−0.095***	−0.105***	−0.103***
	(0.030)	(0.020)	(0.020)	(0.023)	(0.023)
lngdp	0.068	0.238***	0.238***	−0.182***	−0.096
	(0.050)	(0.039)	(0.040)	(0.043)	(0.120)
(lngdp)^2					−0.005
					(0.007)
lnregulation	0.069**	0.046***	0.043***	0.041***	0.040***
	(0.034)	(0.015)	(0.015)	(0.013)	(0.014)
lnenergyten	0.031	0.074**	0.096***	0.033	0.031
	(0.027)	(0.030)	(0.032)	(0.026)	(0.026)
lnfiscal	−0.196***	−0.133***	−0.126***	−0.073***	−0.080***
	(0.044)	(0.024)	(0.025)	(0.026)	(0.027)
lnpolicy	−0.156***	−0.058**	−0.050*	−0.023	−0.023
	(0.055)	(0.028)	(0.028)	(0.024)	(0.024)
Obs	420	420	420	420	420
R^2	0.242	0.285	0.286	0.591	0.592
F test			103.54***	161.77***	161.52***
LM test		1853.00***			
Hausman test			14.92**		
Year test				21.26***	21.19***

*Notes: ***, **, and * indicate significant at 1, 5, and 10% significance level, respectively.*

EMPIRICAL RESULTS

Benchmark Regression

Table 2 reports the regression results based on OLS (Model-1), random effect model (Model-2), fixed effect model (Model-3), and two-way fixed effect model (Model-4, Model-5). According to the joint test of F test, LM test, Hausman test, and year dummy variables, the two-way fixed effect model is the most suitable regression model for the samples studied in this study. Model-5 includes the quadratic coefficient of lngdp, which verifies whether there is a non-linear relationship between industrial development and PM2.5.

The regression results of Model-4 show that the impact of technological innovation on haze pollution is significantly negative. An increase of 1% in the number of green invention patents in the province will lead to a decrease of PM2.5 concentration by about 0.103%. The empirical results show that green technology innovation plays an important role in haze pollution control. Technological innovation may reduce pollutant emissions by improving energy efficiency and improving enterprise cleaner production capacity. The increase in the proportion of the secondary industry also shows a significant negative impact on haze pollution. An increase of 1% of lngdp will reduce the concentration of PM2.5 by about 0.169%. This may be related to the following two aspects: first, China's industrial development has basically abandoned the rough development model dominated by heavy industry, and the high-end manufacturing industry guided by cleaner production has gradually occupied a dominant position. Second, the government plays an important regulatory role in industrial cleaner production. Various types of environmental regulatory means force the industrial sector to reduce the pollution level. The Model-5 results show that the quadratic coefficient of *lngdp* is not significant, which indicates that the relationship between industrial development and haze pollution does not conform to the environmental Kuznets curve.

The control variables also provide valuable information. The investment in industrial pollution control shows a promoting effect on haze pollution. Increasing 1% of *lnregulation* will increase PM2.5 concentration by about 0.036%. This may be because the investment in industrial pollution control cannot make up for the air pollution caused by industrial development. The coefficient of energy intensity is positive. Every 1% reduction of energy intensity will reduce PM2.5 concentration by about 0.022%. This reminds that the government and enterprises should pay more attention to the impact of energy consumption on the environment. The coefficient of fiscal expenditure is significantly negative, indicating that the government intervention has a positive effect on atmospheric governance. Increasing 1% of *fiscal* will promote the PM2.5 concentration to decrease by about 0.071%. Fiscal expenditure may improve the level of cleaner production of industrial enterprises by improving infrastructure, regulating market trade, and promoting science and technology. The coefficient of *lnpolicy* is negative but not statistically significant, indicating that the government's attention to environmental pollution may alleviate haze pollution through administrative means (such as policies and regulations).

Robustness Test and Endogenous Problem

The process of technological innovation is long-term and complex. Green invention patents can show the output level of provinces in green technological innovation, but they may ignore the consideration of technological innovation investment,

TABLE 3 | Robustness test results with *lnrd* and *lntech*.

	RE	FE	Two-way FE	RE	FE	Two-way FE
lnrd	−0.167***	−0.175***	−0.115***			
lntech				−0.050***	−0.053***	−0.059***
lngdp	0.117***	0.106***	−0.210***	0.163***	0.156***	−0.251***
lnregulation	0.045***	0.042***	0.024*	0.029*	0.025	0.029**
lnenergyten	0.074***	0.095***	0.022	0.062**	0.081**	0.033
lnfiscal	−0.157***	−0.148***	−0.044*	−0.147***	−0.138***	−0.041
lnpolicy	−0.091***	−0.084***	−0.036	−0.089***	−0.082***	−0.023
Obs	420	420	420	420	420	420
R^2	0.337	0.338	0.591	0.268	0.269	0.569
F test		111.94***	164.50***			157.16***
LM test	1795.44***			1896.55***		
Hausman test		77.28***				
Year test			17.59***		12.13**	19.83***

TABLE 4 | Robustness test results with *lnpmmax* and *lnpmsum*.

	Lnpmmax			*lnpmsum*		
	RE	FE	Two-way FE	RE	FE	Two-way FE
lnpatent	−0.061***	−0.067***	−0.048**	−0.100***	−0.094***	−0.105***
lngdp	0.173***	0.183***	−0.156***	0.251***	0.237***	−0.183***
lnregulation	0.050***	0.051***	0.035***	0.046***	0.044***	0.042***
lnenergyten	0.074***	0.073***	0.014	0.099***	0.096***	0.033
lnfiscal	−0.141***	−0.142***	−0.053**	−0.128***	−0.125***	−0.073***
lnpolicy	−0.046*	−0.044*	−0.032	−0.048*	−0.050*	−0.023
Obs	420	420	420	420	420	420
R^2	0.309	0.310	0.633	0.294	0.284	0.589
F test		63.22***	110.02***		443.27***	673.77***
LM test	1,682.02***			2,186.27***		
Hausman test		10.36**			265.88***	
Year test			25.18***			21.19***

technology trade, and other factors. Therefore, this study selects the proportion of R&D personnel in the secondary industry (*lnrd*) and technology market turnover (*lntech*) to represent the level of technological innovation investment and the scale of technology trade. *lnrd* represents the development structure and trend of industrial enterprises in our province. The higher the proportion of R&D personnel is, the higher the R&D input intensity is, and the greater the potential of cleaner production in the future is. The expected coefficient of *lnrd* is negative, that is, the proportion of R&D personnel can effectively reduce haze pollution. *lntech* measures the degree of new technology introduction or technology output capability in the production process. The higher the turnover of technology market, the more frequent the flow of clean technology. Enterprises can also achieve cleaner production and reduce pollution through technology trading. The expected coefficient of *lntech* is negative, which means that the increase of technology market turnover will help to reduce PM2.5 concentration.

Table 3 reports the regression results of the random effect model, fixed effect model, and two-way fixed effect model when *lnrd* and *lntech* represent technological innovation. Under the three models, the regression coefficients of *lnrd* and *lntech* are significantly negative. Under the two-way fixed effect model, every 1% increase in the proportion of R&D personnel and the turnover of technology market will reduce the regional PM2.5 concentration by about 0.115 and 0.059%, respectively. Therefore, the robustness test results show that the main conclusion of this study is robust and credible, that is, technological innovation can significantly reduce the regional PM2.5 concentration.

In the previous study, the annual mean value of PM2.5 concentration was analyzed as the explained variable, but the use of the mean value will reduce the attention to the extreme value and total value. Therefore, this study selects the maximum PM2.5 concentration and total PM2.5 (i.e., annual average PM2.5 * provincial administrative area) of each province to represent the extreme value and total pollution of haze pollution in this province. **Table 4** reports the impact of technological innovation on the maximum PM2.5 concentration (*lnpmmax*) and total PM2.5 concentration (*lnpmsum*). The results show that the regression coefficients of technological innovation are significantly negative.

The endogenous problem may be a potential problem affecting the credibility of the empirical conclusion of this study. The root of the endogenous problem is that the disturbance term in the econometric model is related to the

TABLE 5 | Instrumental variable regression results.

	IV (*l.x*)			IV (*lnedu*)		
lnpatent	−0.116***			−0.576***		
lnrd		−0.315***			−1.120***	
lntech			−0.069***			−0.253***
lngdp	0.218***	0.073**	0.129***	0.434***	0.025	0.115*
lnregulation	0.044***	0.055***	0.018	0.060	−0.021	0.130***
lnenergyten	0.062**	0.040	0.039	0.218***	0.081**	0.095***
lnfiscal	−0.122***	−0.143***	−0.138***	−0.661***	−0.539***	−0.406***
lnpolicy	−0.040	−0.099***	−0.079***	−0.167**	−0.295**	−0.028

TABLE 6 | Global Moran's I of PM2.5 concentration.

Year	Moran'I	Year	Moran'I	Year	Moran'I
2005	0.099***	2010	0.079***	2015	0.104***
2006	0.064***	2011	0.068***	2016	0.077***
2007	0.095***	2012	0.061***	2017	0.098***
2008	0.079***	2013	0.086***	2018	0.091***
2009	0.083***	2014	0.099***		

*Notes: ***, **, and * indicate significant at 1, 5, and 10% significance level, respectively.*

explanatory variable and the explained variable at the same time, resulting in the unclear causal relationship between the explanatory variable and the explained variable. Instrumental variable method is an effective method to solve endogenous problems. Existing studies often follow the following ideas in the selection of instrumental variables: first, take the lag term of endogenous variables as instrumental variables; second is to select variables with historical or geographical attributes related to endogenous variables. Based on the existing research, this study selects the following instrumental variables: 1) take the lag phase (*l.x*) of the core explanatory variable (lnpatent, lnrd, lntech) as the instrumental variable; 2) the total number of college graduates (*lnedu*) in each province from 2000 to 2004 is selected as the instrumental variable of technological innovation. First, college graduates are the main source of labor for innovation and R&D in all provinces. The higher the scale of higher education, the higher the technological innovation potential of the representative region. Therefore, the instrumental variable has a significant correlation with endogenous variables. Second, the time of tool variable data is before the main research sample, that is, the disturbance term cannot affect the tool variable, which meets the requirement that the tool variable is independent of the disturbance term.

Table 5 reports the regression results of the instrumental variable method, in which the second to fourth columns are the regression results using the endogenous explanatory variable lag term as the instrumental variable, and the fifth to seventh columns are the regression results taking the total number of graduates of colleges and universities in each province from 2000 to 2004 as the instrumental variable. The regression results show that after controlling the endogenous problem, the impact of technological innovation on PM2.5 concentration is still significantly negative.

Spatial Regression Results

The spatial econometric model includes the spatial interaction of variables and analyzes the impact of haze pollution in surrounding provinces on the province. Before the empirical regression, it is necessary to test the spatial correlation of PM2.5 concentration. The global Moran index measures the spatial correlation between variables. **Table 6** reports the global Moran's I index of PM2.5 from 2005 to 2018. All year indexes are positive and significant at the 1% level.

The local Moran scatter diagram in **Figure 4** shows the spatial agglomeration characteristics of PM2.5 in 2009 and 2018, respectively. Most of the provinces fall in the first and third quadrants, showing the agglomeration characteristics of "high-high" or "low-low." **Table 4** and **Figure 3** show that the use of spatial econometric model is reasonable, and there is a high spatial correlation of haze pollution among provinces. The pollution control of the province is not only affected by the technological innovation and industrial development of the province but also affected by the haze pollution of surrounding provinces.

The regression results based on spatial econometric model are reported in **Table 7**. The results of LR test show that the spatial Durbin model is the most suitable model. The second to fourth columns show the direct effect, indirect effect, and total effect of explanatory variables, respectively. Direct effect refers to the influence of the change of variables in the local province on the local province, which includes both short-term effect and spatial feedback effect. Indirect effect, namely, spatial spillover effect, indicates the influence of the variation of variables in the local province on PM2.5 concentration in surrounding provinces. The total effect is the sum of direct effect and indirect effect, which describes the total impact of variable changes on all sample provinces. The coefficient of spatial lag term of PM2.5 is positive and significant at the level of 5% (coefficient = 0.170, p-value<0.05). It can be explained from the following two aspects: on the one hand, the natural conditions of neighboring provinces are similar, and haze will affect the surrounding provinces through atmospheric flow. On the other hand, neighboring provinces have similar economic development and energy structure, so they will show similar characteristics in air pollution. This reminds the government that in the process of sustainable development, it not only needs to improve the governance level of the province but also needs "joint prevention and control" among the provinces. Only by strengthening cooperation among provinces can the emission

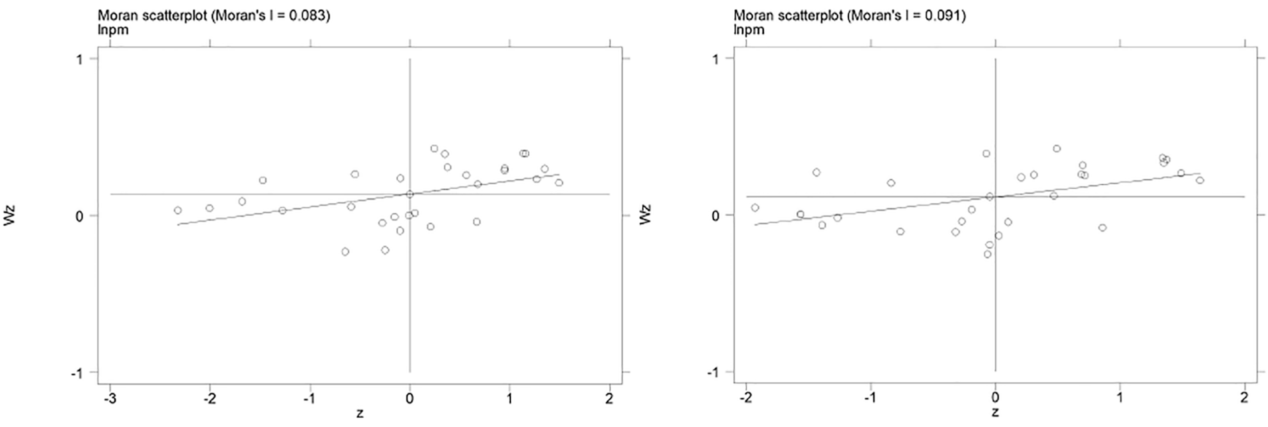

FIGURE 4 | Local Moran'I of PM2.5 concentration.

TABLE 7 | Estimation results of Spatial Durbin Model.

	Direct effect	Indirect effect	Total effect
lnpatent	−0.086***(0.023)	−0.157*(0.129)	−0.243**(0.131)
lngdp	−0.222***(0.042)	−0.420 (0.276)	−0.642**(0.277)
lnregulation	0.047***(0.013)	0.176*(0.100)	0.224**(0.105)
lnenergyten	0.014 (0.025)	−0.058 (0.119)	−0.044 (0.131)
lnfiscal	−0.068***(0.026)	−0.409**(0.195)	−0.476**(0.192)
lnpolicy	−0.012 (0.023)	0.111 (0.170)	0.099 (0.180)
W*PM2.5		0.170**(0.110)	
Obs	420	R^2	0.351
Time fixed	YES	ind fixed	YES
LR test for SAR	11.88*	LR test for SEM	13.73**

reduction effect of scientific and technological innovation be maximized.

The direct and indirect effects of the proportion of R&D personnel investment are significantly negative, and the direct and indirect effects of green patented inventions are negative and significant at least at the level of 10%. An increase of 1% in the number of green invention patents in the province will reduce the PM2.5 concentration in the province and surrounding provinces by about 0.086 and 0.157%, respectively. The total effect was significantly negative (the coefficient was −0.243, p-value<0.10), indicating that the investment in technological innovation had a negative impact on the concentration of PM2.5 in all provinces. The empirical results confirm that there is technology spillover effect among provinces. This study believes that technology, as a non-competitive factor of production, may form technology spillover through the following ways: first, the cross regional trade between upstream enterprises and downstream enterprises in the industrial chain and technology will realize the flow between provinces through enterprise cooperation, technology transaction, products and other media; second, the migration of R&D personnel between regions due to family, work, and other reasons leads to the flow of technical personnel between provinces. The aforementioned ways make the technological innovation achievements of the province flow into the surrounding provinces, so as to alleviate the haze pollution in all sample areas.

Among the control variables, industrial development shows a significant negative direct effect (similar to the results of Model-4 in **Table 2**) and a non-significant negative indirect effect, indicating that the industrial development of the province still has a certain negative impact on PM2.5 in surrounding provinces. The process of China's industrial development is accompanied by the inter provincial flow of resources and commodities, resulting in the characteristics of spatial agglomeration. On the one hand, the industrial developed provinces fully absorb the capital and technology of the surrounding provinces, forming the scale effect. This is conducive to the green and sustainable development of the province and may form the phenomenon of haze pollution decreasing with the industrial development. On the other hand, the flow of capital and technology to central provinces will weaken the sustainable development potential of resource exporting provinces, namely, "siphon effect." The siphon effect leads to that the resource exporting provinces can only develop their industries by maintaining the mode of "high energy consumption and high pollution," and the lack of technical support will make it difficult for them to get rid of the status of "pollution paradise," and finally make the industrial development show a unsignificant negative indirect effect. In addition, this study also empirically analyzes the existence of spatial spillover effect when lnrd and lntech are used to measure the level of technological innovation. The results are reported in the **Supplementary Table S2**. Compared with the results in **Table 6**, there is no difference in coefficient direction and significance.

Threshold Regression Results

In the previous study, we analyzed the topic of "whether technological innovation alleviates haze pollution." However, the conclusions in the previous study can only prove that technological innovation has a significant negative effect on haze pollution on the whole but lack of analysis on the heterogeneity of negative effects under different degrees of economic development. Therefore, we need to introduce the

TABLE 8 | Threshold significance test.

	Single threshold	Double threshold	Triple threshold
F-value	15.337	11.488	2.232
p-value	0.000	0.001	0.119

*Notes: ***, **, and * indicate significant at 1, 5, and 10% significance level, respectively.*

threshold effect model for the empirical analysis. This study selects GDP as the threshold variable to represent the level of economic development. Theoretically, the emission reduction effect of technological innovation exists in any stage of economic development, but there are differences in different stages. First, the primary stage of economic development is dominated by the development mode of high energy consumption and high pollution. The degree of technological innovation participating in cleaner production is low, and the haze pollution is the most serious. In this stage, the haze governance benefits of technological innovation are the highest. Second, when the economy develops to the next stage, haze governance needs to be realized through optimizing the energy structure, industrial upgrading, and other deep-seated ways, so the benefits of haze governance of technological innovation should be lower than the previous stage. Finally, in economically developed provinces, technological innovation has a scale effect, forming an economic model with high-tech industry and service industry as the pillar. The injection of cleaner production technology will play a greater role through the scale effect. According to the research of Hansen (1999) and Kassouri et al. (2021b), the single threshold model is set as follows:

$$PM_{it} = \gamma_0 + \gamma_1 TEC_{it}\left(eco_{it} < \phi\right) + \gamma_2 TEC\left(eco_{it} > \phi\right) + \delta X_{it} + \varepsilon_{it}. \tag{7}$$

In **formula (7)**, eco_{it} represents the threshold variable, φ represents the threshold value, and TEC represents the core explanatory variables (*lntech*). γ_1 and γ_2 are the most concerned coefficients in threshold regression, and the difference between them reflects the change of haze control effect of technological innovation when the threshold variable exceeds the threshold value. However, the single threshold cannot fully reflect the actual stage of economic development, so the possibility of double threshold, three threshold, or even multiple thresholds also needs to be discussed. The double threshold is as follows:

$$PM_{it} = \gamma_0 + \gamma_1 TEC_{it}\left(eco_{it} < \phi_1\right) + \gamma_2 TEC\left(\phi_1 < eco_{it} < \phi_2\right) + \gamma_3 TEC\left(eco_{it} > \phi_2\right) + \delta X_{it} + \varepsilon_{it}. \tag{8}$$

The meaning of elements in **formula (8)** is the same as that in **formula (7)**, but the relationship between γ_1, γ_2, and γ_3 can indicate whether the haze control effect of technological innovation will present "N-shape" or "inverted N-shape" curve relationship according to the change of economic development level. In terms of measurement method, according to Hansen's 1999) research, we should test the number of threshold by measurement method before the empirical analysis. **Table 8** reports the test results of single threshold, double threshold, and triple thresholds. The results show that the double threshold model is the most suitable model when the provincial GDP is taken as the threshold variable.

Table 9 reports the regression results of the threshold effect model. In the single threshold model, the threshold value is 974.1 billion yuan/RMB; when the provincial GDP exceeds 974.1 billion yuan, the impact of technological innovation on PM2.5 concentration will change. In the double threshold model, the threshold values are 974.1 and 1,646.9 billion yuan/RMB, respectively; when the GDP of the whole province exceeds 1,646.9 billion yuan, the impact of technological innovation on PM2.5 will change again. The regression coefficients in **Table 4** show that technological innovation always has a significant negative impact on PM2.5 concentration, but there are differences with different stages of economic development.

In the double threshold model, *lntech* represents technological innovation, which shows the characteristics of "high-low-high" effect of technological innovation on haze pollution control. In the first stage, when the province's annual GDP is less than 974.1 billion yuan, the increase of *lntech* by 1% will lead to the decrease of PM2.5 concentration by 0.093%. At this stage, the province's economic volume is small, and the demand of "pursuing economic benefits" is higher than that of green sustainable growth. Therefore, the government often adopts the

TABLE 9 | Threshold model result.

Model	*lnpatent*		*lnrd*		*Lntech*	
	Single threshold	Double threshold	Single threshold	Double threshold	Single threshold	Double threshold
lngdp	0.190***	0.186***	0.043*	0.054*	0.092***	0.102***
lnregulation	0.058***	0.052***	0.054***	0.051***	0.035**	0.035**
lnenergyten	0.114***	0.107***	0.111***	0.107***	0.078**	0.070**
lnfiscal	−0.134***	−0.122***	−0.157***	−0.150***	−0.138***	−0.127***
lnpolicy	−0.041	−0.047*	−0.075*	−0.076**	−0.080***	−0.076***
PM2.5 (eco<9,741)	−0.110***	−0.093***	−0.181***	−0.170***	−0.060***	−0.053***
PM2.5 (eco>9,741)	−0.088***		−0.156***		−0.050***	
PM2.5 (9,741 < eco<16,469)		−0.070***		−0.144***		−0.045***
PM2.5 (eco>16,469)		−0.084***		−0.153***		−0.052***
Obs	420	420	420	420	420	420

*Notes: ***, **, and * indicate significant at 1, 5, and 10% significance level, respectively.*

TABLE 10 | Regression results in different regions.

	Eastern region			Central region			Western region		
	Direct	Indirect	Total	Direct	Indirect	Total	Direct	Indirect	Total
lnpatent	−0.030*	−0.220*	−0.248*	−0.040**	−0.271***	−0.311**	−0.026*	−0.130	−0.156
lngdp	−0.134*	−0.020	−0.154	−0.420***	−0.630**	−1.049***	−0.025	−0.355	−0.380
lnregulation	0.025	0.068	0.093	0.059**	−0.070	−0.011	0.011	0.023	0.034
lnenergyten	−0.440***	−0.316	−0.756	0.081	0.019	0.099	0.007	−0.177	−0.171
lnfiscal	−0.039	−0.284**	−0.324**	0.078	1.361	1.440	−0.020	1.045***	1.025***
lnpolicy	0.005	−0.163	−0.157	−0.041	0.005	−0.036	−0.041	−0.098	−0.139
W*PM2.5	0.128*			0.230**			0.098*		
Obs	140			154			126		
R^2	0.322			0.173			0.205		

*Notes: ***, **, and * indicate significant at 1, 5, and 10% significance level, respectively.*

development mode of "abatement after pollution," and resource intensive industries become an important economic growth point. This kind of development mode will lead to the formation of "pollution haven" or "pollution paradise" in the province. At this stage, the economic society presents the characteristics of "high energy consumption-high pollution-high growth-low innovation." The degree of technology innovation participating in cleaner production is the lowest, so the space of emission reduction is the largest. In the second stage, when the province's annual GDP is between 974.1 billion yuan and 1,646.9 billion yuan, an increase of 1% in *lntech* will reduce PM2.5 concentration by about 0.070%, which is slightly lower than the haze control benefits of technological innovation in the first stage. At this stage, the economic volume has begun to take shape, economic benefit is no longer the only goal pursued by the society and the people, and the development is in the stage of transforming from resource-oriented mode to green sustainable development. At this stage, haze control faces more bottlenecks: On the one hand, economic growth cannot completely get rid of the "high energy consumption high pollution" characteristics of the previous stage, and industrial upgrading and energy structure optimization need more capital and technology investment; on the other hand, technological innovation investment is facing more output dilemma, and the application of cleaner production technology needs longer research cycle and time and higher capital investment. To sum up, there will be a dilemma of "high-tech input but low output" and low innovation efficiency in this stage. In the third stage, when the province's annual GDP exceeds 1,646.9 billion yuan, an increase of 1% in *lntech* will reduce PM2.5 concentration by 0.084%, which is higher than that in the second stage but lower than that in the first stage. At this stage, the transformation to sustainable development mode is basically completed. The high-tech industry and green manufacturing industry have become the driving force of the economy, and the backward production capacity with high pollution has been basically eliminated. In the process of social development, perfect infrastructure and public transportation reduce the per capita energy consumption and provide a new way for haze pollution control. Therefore, cleaner production technology will be widely used in agriculture, industry, service industry, and other fields.

Analysis of Regional Differentiation

The Chinese mainland has a huge area with diverse geographical features and climatic characteristics. In terms of resource endowment, the eastern coastal areas are rich in water resources, while the central and western regions are rich in fossil fuel resources. Geographical differences lead to significant heterogeneity in PM2.5 concentration (as shown in **Figure 3**) and economic development characteristics in eastern, central, and western regions. Therefore, it is of great significance for government policy-making to analyze the differences of the impact of technological innovation on haze pollution control in different regions. In this study, 30 provinces are divided into eastern, central, and western regions, and the fixed effect model and spatial Durbin model are used for the regression analysis. The results are reported in **Table 10**.

The spatial concentration of PM2.5 showed the characteristics of central region > eastern region > western region. In the central region, every 1% increase of PM2.5 concentration in the surrounding provinces will lead to a 0.230% increase of PM2.5 concentration in the local province, which is slightly higher than 0.128% in the eastern region. In the western region, a 1% increase in PM2.5 concentration in the surrounding provinces will only lead to a 0.098% increase in PM2.5 concentration in the local province. Combined with **Figure 3**, the haze pollution control in central and eastern provinces is more difficult and pressure is higher. Due to the denser cities and flatter terrain in the eastern and central regions, PM2.5 will have a more serious spillover effect on the surrounding provinces through atmospheric flow, so haze control is facing greater obstacles. This reminds that the central government needs the joint efforts of all provinces in the future sustainable development, and the development mode of "pollution before treatment" should not exist in any province.

In the haze control effect of technological innovation, the central region is significantly higher than the eastern and western regions, the coefficients of *lnpatent* is significantly negative. The results show that the technological innovation central provinces can significantly reduce the PM2.5 concentration. Achieving green economic growth through technological innovation is an important means for the central region in the future. The *lnpatent* in the western region also shows a significant haze control effect, but it is lower than that in the central region. This may be due to the low level of innovation in the western region except for the core cities, which makes it difficult to play the scale effect. In the eastern region, technology trading shows significant haze emission reduction effect. This shows that cleaner production technology can be applied to more industries and enterprises through trade means to achieve a wider range of cleaner production. For the spatial spillover effect of technological innovation, *lnpatent* shows a significant positive spillover effect in the central and eastern regions. In the central and western regions with poor innovation foundation, increasing the scale of technology trade and encouraging technology introduction are the main means to improve the cleaner production capacity in the short term.

CONCLUSIONS AND POLICY RECOMMENDATIONS

By using the PM2.5 concentration data of Dalhousie University, the data of 30 provinces in China from 2005 to 2018, and the panel data model, threshold effect model, and spatial Durbin model, this study empirically analyzes the effect of technological innovation on haze control with R&D personnel input and technology market turnover representing the level of technological innovation. The main conclusions are as follows: 1) technological innovation has a negative impact on PM2.5 concentration. Under the two-way fixed effect model, the increase in green invention patent by 1% will lead to the decrease in PM2.5 concentration by about 0.103%. Moreover, technological innovation shows a positive spatial spillover effect, and the improvement of the technological innovation level in the province will significantly reduce the PM2.5 concentration of surrounding provinces. 2) Haze pollution shows the characteristics of "high-high" or "low-low." The PM2.5 concentration increase of 1% in surrounding provinces will lead to a PM2.5 concentration increase of about 0.170% in the province. 3) In general, industrial growth significantly relieved the haze pollution. Under the spatial Durbin model, the 1% growth of industrial GDP in the province will reduce the PM2.5 concentration of the whole sample by about 0.642%. 4) With improvement in the level of economic development, the impact of technological innovation on PM2.5 concentration shows a "high-low-high" trend. When the province's annual GDP is less than 974.1 billion yuan, the role of technological innovation is the largest, and when the GDP is between 974.1 billion yuan and 1,646.9 billion yuan, the role is the smallest. 5) The haze control effect of technological innovation shows significant regional differences. The haze control effect is the largest in the central region and the smallest in the western region.

According to conclusions, the following policy recommendations are put forward: 1) Haze pollution control is not only the task of one province but also needs the cooperation of all provinces. The establishment of "joint prevention and control" system of haze pollution is the fundamental way to maximize cleaner production technology. If there is serious haze pollution in one or several provinces, it will destroy the sustainable development of the surrounding provinces and lead the whole region into a pollution dilemma. Therefore, the central government should be alert to the emergence of "pollution refuges." 2) Technological innovation is an important driving force to promote sustainable development, and it plays a positive role in promoting haze governance at any stage of economic development. The government and enterprises should increase R&D investment, stimulate the vitality of scientific research institutions and universities in the development of new technologies, and accelerate the application of new technologies in production and life. Technological innovation has the highest efficiency in haze control in the underdeveloped stage, which shows that economic growth should not be an excuse to give up pollution control, and technological innovation should be adhered to at any stage. The technology spillover effect reminds the government that it is important to eliminate trade barriers and promote technology trade. 3) Industrial development needs to accelerate the transformation from the resource-based development mode to green sustainable development mode. We should increase the proportion of high-tech industry and high-end manufacturing industry in industrial development and improve the sustainable development ability of traditional manufacturing industry. 4) Haze control needs the efforts of all aspects of economic development. Reducing energy intensity, expanding financial support, and strengthening environmental regulation are effective auxiliary means of pollution control.

ETHICS STATEMENT

This study involves the macro-data of human economy and society. All the data are from the official statistical yearbook and the open data by Dalhousie University. The data collection process is in line with the ethical and moral standards. The research method of this study is the panel threshold model and spatial econometric model, and there is no need for ethical approval and animal experiment content. The authors guarantee that the process, content, and conclusion of this study do not violate the theory and moral principles.

AUTHOR CONTRIBUTIONS

WS was mainly responsible for data collation, empirical analysis, model building, research route, theoretical analysis, and wrote manuscript. LZ provided software operation guidance, helped with manuscript modification, and wrote the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.800460/full#supplementary-material

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