The Spatial Effect of Green Finance on PM2.5 —— Analysis of Mediating Effect Based on Technological Innovation

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The Spatial Effect of Green Finance on PM2.5
——Analysis of Mediating Effect Based on Technological Innovation

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Abstract

This paper uses technological innovation as a mediating variable, based on 30 provincial panel data in China from 2011 to 2019, and uses the spatial Durbin model to study the spatial effect of green finance on PM2.5. It is found that the development of green finance not only inhibits local PM2.5 emissions, but also drives the development of green finance in the surrounding areas through the spillover effect of green finance, thereby inhibiting PM2.5 emissions in the surrounding areas. Through empirical research, this paper also finds that technological innovation has a significant mediating effect on the reduction of PM2.5 by green finance. At the key stage of green transformation in China, green finance can optimize the allocation of financial resources and provide financial support for technological innovation of enterprises, thereby reducing energy consumption and pollution emissions through technological innovation and ultimately inhibiting PM2.5. This study links green finance and PM2.5 from the perspective of space, and explores the channels to improve air quality in China, which is conducive to accelerating the green transformation of China’s economy and improving the human living environment.

Keywords: PM2.5; Green finance; Technological innovation; Spatial Durbin model; Mediation model.

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1. Introduction

Haze pollution caused by PM2.5 threatens human health and causes environmental pollution to a large extent (Cao et al., 2018; Shao et al., 2020; Shi et al., 2021). The term PM2.5 refers to airborne particles having a diameter of 2.5 microns or smaller, which are the primary cause of haze and one of the key indicators of the level of air pollution (World Health Organization, 2021). PM2.5 is very small in the atmosphere, but has a substantial effect on visibility, air quality and the environment (Zhou et al., 2012). Therefore, the treatment of PM2.5 has become one of the important measures to protect the living environment of human health (Pui et al., 2014). Many medical studies have shown that PM2.5 is positively correlated with human diseases, especially respiratory diseases and cardiovascular diseases. After forty years of reform and opening up, the quality of life of the Chinese people has vastly increased, and the economy has achieved remarkable success (Zhong et al., 2021). While the economy has achieved rapid development, China's environmental situation is deteriorating (Liu et al., 2021). In 2013, the most serious haze weather in the history of 52 years broke out. Until now, haze pollution is still the key problem to alleviate air pollution (Huang et al., 2017; Feng et al., 2019; Li et al., 2021).

In 2021, the State Council of the Central Committee of the Communist Party of China issued the “Opinions of the State Council of the Central Committee of the Communist Party of China on In-depth Fighting against Pollution”. It required that the direction should be unchanged, the intensity should not be reduced, and the precise, scientific and legal pollution control should be highlighted. It should take the synergistic effect of reducing pollution and reducing carbon as the general starting point, take the synergistic control of PM2.5 and ozone as the main line, strengthen the synergistic control of multi-pollutants and regional joint defense and control, focus on solving the prominent environmental problems around the people, and promote high-quality economic development and low-carbon green transformation of the whole society. It is proposed that by 2025, the PM2.5 concentration in prefecture-level and above cities will decrease by 10 %, the ratio of days with good air quality will reach 87.5 %, and the heavy pollution weather will be basically eliminated. Therefore, the task of reducing PM2.5 concentration has a long way to go.

PM2.5 mainly comes from vehicle exhaust emissions, high energy-consuming industrial fuels and so on (Xu et al., 2018). In the early days, China mainly relied on the development of energy-based industries to drive the economy, which caused the neglect of environmental problems and increased the degree of PM2.5 pollution to some extent (Wu et al., 2019). The rapid growth of the green industry in China's economic development can displace some sectors with high energy consumption, low efficiency, and high pollution (Song et al., 2021). However, it is challenging for new green businesses to find affordable financial backing, making it challenging for them to properly fulfill their role in reducing pollution (Du et al., 2022). The emergence of green finance can well solve the problems of financing difficulties and expensive financing of green enterprises. Numerous economic operations that assist environmental protection, climate improvement, energy structure optimization, and resource utilization efficiency are all part of the green finance (Jin et al., 2021; Volz et al., 2018). Therefore, green finance can provide high-quality financial support for green enterprises, promote green enterprises to expand their scale and quantity, achieve green upgrading and optimization of industries, inhibit PM2.5 emissions, and alleviate air pollution, so as to promote green economic development (Liu et al., 2021; Yang et al., 2021). It can be seen from Fig. 1 that the concentrations of PM2.5 were relatively high in 2011 (2a) and 2015 (2b), and the concentrations in the central regions such as Shanxi Province, Hebei Province, Henan Province and Shandong Province were the most serious. The development of green finance in 2011 (1a) and 2015 (1b) in coastal cities such as Jiangsu Province, Shanghai, Zhejiang Province, Guangdong Province, the most developed. In 2019 (1c), the green finance in coastal cities continued to develop, and the green finance in Hubei Province, Hunan Province, Shanxi Province and other
places in the central region began to rise and develop rapidly.

Figure 1 Green Finance Index and PM2.5 Concentration Distribution Map

However, technological innovation is an endogenous variable to promote environmental quality
improvement and has a mediating effect on green finance to reduce PM2.5 emissions (Chen et al., 2021), and it includes adopting new production methods, production processes and equipment to manufacture new products, or upgrading the original production technology. Therefore, technological innovation can improve production capacity by improving productivity, thus forming scale effect and saving resources (Cheng et al., 2021). With the progress of technology, green cleaning technology has also been developed. Using clean technology to replace pollution technology can inhibit PM2.5 emissions, thereby reducing air pollution. Technological innovation usually has great uncertainty. In order to avoid risks, financial institutions are generally unwilling to lend funds to innovative enterprises, which causes such enterprises to be unable to obtain low-cost and high-quality funding sources, resulting in the growth of innovative enterprises. Green finance makes a large number of high-quality funds flow into these innovative enterprises through green securities and green credit, which makes these enterprises get financial support for technological innovation, so as to promote the improvement of production efficiency, the green upgrading of energy and the green development of economy, so as to reduce the emissions of PM2.5 and other pollutants, realize the 14th Five-Year Plan, accelerate the promotion of green development, and promote the harmonious coexistence of human and nature (Yu et al., 2021).

From the research progress in related fields, some researchers describe the spatial distribution and spatial correlation characteristics of PM2.5 based on spatial statistics technology, and some apply time series statistics and econometric technology to describe the temporal variation of PM2.5, which confirms that PM2.5 can realize cross-border transmission (Cheng et al., 2017). The continuous expansion of PM2.5 pollution boundary makes it impossible to improve the urban air quality in the polluted areas. The dynamic correlation between multiple cities constitutes a complex network with cities as nodes. Only from the perspective of administrative divisions, it is difficult to effectively solve the current increasingly serious regional PM2.5 pollution problem by considering the environmental management and pollution control mode of individual PM2.5 reduction (Liu et al., 2021). In addition, green finance can use its function of cross-regional transactions to optimize resource allocation at the spatial level, provide financial support for green R&D activities of enterprises, so as to promote the coordinated development of regional technological innovation, and optimize the industrial structure through technical effects and reduce energy consumption to improve the efficiency of regional haze governance, and ultimately help to reduce the total amount of PM2.5 (Fang et al., 2022). Therefore, this paper uses the spatial Durbin model to study the spatial impact mechanism of green finance on PM2.5.

The contributions of this study are as follows: firstly, this paper studies the impact of Green Finance on PM2.5 based on spatial model. Secondly, this study also analyzes the mediating effect of technological innovation on the relationship between green finance and PM2.5 through the mediating effect model. This study is conducive to promoting the coordinated development of haze control among Chinese provinces, and provides a reference for improving the efficiency of haze control and improving air quality in China.

The layout of this paper is as follows: the second part combs the relevant references. The third part mainly introduces the research methods and variables. The fourth part presents the result analysis. The fifth part summarizes the whole article and puts forward policy recommendations.

2. Literature Review

2.1 Green Finance and PM2.5 Emissions

Green finance has emerged as a brand-new area of study for the financial sector in order to achieve the environmentally friendly and sustainable growth of China's economy. Financial activities are closely related to the natural environment, and the financial industry has a significant impact on the nation's sustainable development (Barua et al., 2020). In view of the increasingly serious environmental problems and the single financing channel of environmental industry, scholars began to think about how to protect the environment
from the perspective of financial inducement, which accelerating China’s attention to green finance. The sector of haze governance has benefited from the growth of green financing, mainly reflected in reducing PM2.5 emissions (Zeng et al., 2022). After the introduction of the concept of “green investment”, a large number of industrial capital flows, and the market needs to guide, regulate and use capital to promote reliable technological projects. Zheng et al. (2022) incorporated green finance into the framework of environmental regulation analysis to explore how the interaction between green finance and environmental regulation, industrial structure and technological level affects haze governance. Gao et al. (2022) constructed the spatial Durbin model and concluded that green finance can improve the haze governance effect together with environmental regulation, structural effect and technical effect. The haze control industry is an emerging industry with the core of solving the haze problem and reducing PM2.5 concentration (Gan et al., 2021). In 2016, China implemented the 'air pollution control regulations' to guide specific industries to connect with professional technology, closely integrate the haze governance industry with the green finance industry, and create more new and efficient haze governance channels. Wang et al. (2022) employed the semi-parametric difference method to find that the development of green finance has greatly alleviated the industrial emissions of 290 cities in China. They stressed that the government should accelerate innovative services for green finance. On the one hand, green clean energy can be greatly developed with financial support from green finance and can promote the transformation of energy consumption structure from traditional fossil fuel energy consumption to green renewable energy consumption; On the other hand, for loans for carbon-intensive activities, green finance can well limit the number within a certain range, so as to reduce the proportion of bank loans for carbon-intensive activities (Li et al., 2021; Yang et al., 2022). Therefore, green finance can well reduce the emission of exhaust gas generated by energy consumption and reduce the formation of PM2.5 from the source. In addition, in terms of pollution control mechanism, green finance and environmental regulation have both differences and strong complementarity. Green finance is critical to the growth of the haze control business in different regions for the purpose of reducing PM2.5 emissions (Shi et al., 2017). In addition, green finance has a diffusion effect, which can also promote the financial development of the surrounding areas. Therefore, green finance not only inhibits local PM2.5 emissions, but also the energy and industrial structure of the surrounding areas are optimized, so the PM2.5 emission problem is greatly reduced, and the pollution of haze on air is alleviated (Li et al., 2022).

To sum up, this paper gives hypothesis 1: Green finance can inhibit PM2.5 emissions in the local region and the regions around it.

2.2 Green Finance and Technological Innovation

Enterprises need sufficient financial support to achieve the goal of innovation. Financing difficulty and high financing cost are still the key problems restricting the development of enterprises, especially SMEs (Lee et al., 2015). First of all, from the perspective of financing costs: owing to the features of high capital expenditure, high risk, and a lengthy cycle of enterprise technology innovation, enterprise technology innovation is facing greater uncertainty (Wen et al., 2022). Small and medium-sized businesses constitute a significant share of the overall number of businesses, and such enterprises have low debt capital risk tolerance, and the general financial institutions are unwilling to invest in innovation projects of such enterprises in consideration of risk control costs, resulting in high financing costs of such enterprises. The development of green finance provides guarantee for technological research and innovation of enterprises, and makes external investors more willing to provide financial support for R&D of enterprises, thus promoting the innovation input and output of enterprises (Shi et al., 2022). If this mechanism exists, it can be speculated that for enterprises with strong external financing constraints, the development of green finance has a greater impact on their innovation activities. Some enterprises that meet the local green financial environmental
standards are more likely to obtain financing, effectively improve financing efficiency, reduce financing costs and improve the availability of funds (Jin et al., 2021). Zhang et al. (2021) analyzed 152 environmental listed companies in China, and found that green finance encourages R&D investment and promotes technological innovation. However, in the context of the rapid development of green finance, the operating costs of enterprises not in line with green development are relatively increased, resulting in a shortage of funds. The funds used for technological innovation will be compressed, and enterprises will also face the lack of funds and make technological innovation blocked. This will lead to the gradual elimination of enterprises with high energy consumption, low efficiency and high pollution, and the rapid development of enterprises in line with the green concept, so as to accelerate the upgrading of the industrial structure, improve output, offset the cost of environmental regulation, and improve the market competitiveness of enterprises in the long run (Cai et al., 2020). Therefore, green finance will strengthen technological innovation of enterprises to broaden green financing channels, achieve environmental standards and better attract green investment. Based on the research of Lv, C. (2021) and Shao et al. (2020), this paper believes that green finance can affect the matching of risk and return of innovation behavior by allocating capital and the expected income structure that affects innovation behavior, so as to guide enterprises to choose technological innovation behavior.

In conclusion, the second hypothesis 2 put out in this study is that green finance significantly encourages technological innovation.

2.3 Technological Innovation and PM2.5 Emissions

Technological innovation to promote the formation of a new global energy pattern is one of the key factors to achieve green economic development. Firstly, technological innovation can restrain PM2.5 emission from improving energy efficiency and changing energy consumption structure. (1): The improvement of technological innovation can promote enterprises to use decarbonization technology in the production process to achieve the effect of energy saving and emission reduction, so as to improve green total factor productivity, reduce energy consumption and PM2.5 emissions. Chen et al. (2022) concluded that from 1990 to 2016, technological innovation supported 73 developing countries to improve energy efficiency, which proved that technological innovation could reduce carbon footprint and environmental pollution. (2): In order to improve the regeneration capacity of renewable energy and realize the transformation and upgrading of green and clean energy, China must vigorously develop technological innovation. Shen et al. (2020) believe that innovation in renewable energy can significantly reduce consumption of traditionally consumed energy sources. Sharma et al. (2021) argued that energy innovation boosted renewable energy use in oil-poor nations. Secondly, technological innovation can speed up the replacement of traditional polluting enterprises to green enterprises, thus crowding out the traditional resource-based enterprises. Due to the rapid development of green finance, more resources flow to green environmental protection enterprises, and the traditional pollution enterprises are difficult to obtain funds (2022). Therefore, these traditional polluting enterprises must carry out green upgrading through technological innovation, so as to avoid being eliminated by the market. Specifically, it is a common way to save energy and reduce consumption for enterprises to carry out technical transformation of equipment with large energy consumption or use funds to purchase equipment with higher quality from outside to achieve high efficiency and low consumption. At the same time, technological innovation can save relatively expensive production factors, thereby reducing the cost of energy use. Efficient use of energy, reduce energy consumption, is bound to reduce waste emissions and haze pollution, making polluting enterprises quickly achieve green upgrading (Ouyang et al., 2020).

To sum up, this study provides the hypothesis 3: technological innovation will significantly inhibit PM2.5 emissions.

3. Methodology And Data
3.1 Methodology

3.1.1 OLS panel regression model construction

In order to verify the above assumptions, this paper firstly constructs a basic linear model (OLS) to explore the impact of green finance on PM2.5. The model is shown as follows:

\[
\text{pm2.5}_{it} = a_0 + \beta_1 gfi_{it} + \beta_2 pop_{it} + \beta_3 financeim_{it} + \beta_4 gap_{it} + \beta_5 gtfp_{it} + \beta_6 eri_{it} + \varepsilon_{it}
\]  

In its formula (1), subscript \(i\) is the area and \(t\) is the year; \(pm2.5_{it}\) refers to the explained variable and represents the particles less than or equal to 2.5 microns in diameter; \(gfi_{it}\) denotes green financial index; \(a_0\) is a constant, \(\beta_1 \sim \beta_6\) are the coefficients of the regression variables; \(pop\) represents the natural population growth rate; \(financeim\) represents financial development level; \(gap\) represents the urban-rural income gap; \(gtfp\) is green total factor productivity; \(eri\) is local environmental regulation index and \(\varepsilon\) is the random error term.

3.1.2 Construction of Spatial Durbin model

Firstly, spatial autocorrelation model regression must be carried out before spatial model application to judge the applicability of the model. Diniz-Filho et al. (2003) proposed that almost all things have spatial dependence. This paper calculates global Moran’s I using geographic distance matrix. The equation is presented in equation (2):

\[
\text{Moran's I} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij} (Y_i - \bar{Y})(Y_j - \bar{Y})}{s^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}}
\]  

\[
s^2 = \frac{1}{n} \sum_{i=1}^{n} (Y_i - \bar{Y})^2, \quad \bar{Y} = \frac{1}{n} \sum_{i=1}^{n} Y_i
\]

\(Y_i\) represents the value of region \(i\); \(n\) is the number of regions in total; \(W_{ij}\) represents the spatial weight matrix. There is a positive spatial correlation; when, there is a spatial negative correlation; \(I = 0\) indicating no spatial correlation, and \(-1 \leq I \leq 1\).

Spatial weight matrix \((W = [W_{ij}])_{n \times n}\) reflects the dependence of individuals in space and is the basis for constructing spatial econometric models. The commonly used spatial weight matrix mainly includes economic distance matrix, geographical distance matrix and 0-1 matrix. This paper mainly studies the spatial correlation between PM2.5 and green finance. Since PM2.5 is mainly affected by geographical location, natural condition endowment and industrial structure, this paper selects the geographical distance matrix as the basic weight matrix. At the same time, because the 0-1 matrix can be a good analysis of the spillover effect of adjacent areas, this paper selects the 0-1 matrix as a secondary matrix to test the robustness of the spatial regression results.

Secondly, this paper constructed Spatial Durbin Model (SDM) as spatial econometric model. The spatial Durbin model is a generalization of the spatial error model (SEM) and the spatial lag model (SLM) (SLM). The Hausman test tells us whether we select fixed effect or random effect. Next, the Likelihood Ratio (LR) test is used to evaluate if the model has a spatial or temporal fixed effect. The Lagrange Multiplier (LM) and Wald test can help us determine whether the SDM model can degenerate into SLM or SEM and which model
is the best (Liu and Song, 2020), respectively, and then we can choose the most suitable spatial model. In order to study the spatial impact of green finance on PM2.5, we refer to Yan et al. (2022), Bao et al. (2021), Shao (2020) et al., and establish a spatial Durbin model. The specific formula (3) shows:

\[ pm2.5_{it} = \rho \sum_{j=1}^{n} W_{ij} pm2.5_{jt} + \beta_1 gf_{it} + \theta_1 \sum_{j=1}^{n} W_{ij} gf_{jt} + \lambda X_{it} + \mu_i + \lambda_t + \epsilon_{it} \]  

In equation (3), \( i \) represents area, \( t \) denotes year; \( W \) is \( n \times n \) order geographical distance spatial weight matrix; \( \rho \) is the spatial autocorrelation coefficient of the explained variable to measure the possible spatial correlation of the explained variable between regions; \( \beta \) is the regression coefficient of explanatory variables, which measures the influence of explanatory variables on explained variables in the region; \( \theta \) is the spatial regression coefficient of explanatory variables to measure the spatial spillover effect of explanatory variables; \( X_{it} \) denotes control variables, includes population growth (pop), financial development (financeim), urban-rural income gap (gap), green total factor productivity (gtfp), local environmental regulation index (eri); \( \mu_i \) is space fixed effect, \( \lambda_t \) is time fixed effect, \( \epsilon_{it} \) is random error term.

### 3.1.3 Construction of mediating effect model

The mediating effect model consists of mediating variables, independent variables and dependent variables. The relationship between the three is: if the core variable X has a certain influence on the explained variable Y through a certain variable M, M is called the intermediary variable of X and Y. Mediation effect model can link the original research on the same phenomenon together, so as to find out the reasons behind the phenomenon. In order to explore the role of technological innovation (rdsl) in the impact mechanism of green finance on pm2.5, this paper constructs a mediating effect model, and the specific impact mechanism is as Fig.2 follows:

![Figure 2 Mediating Effect Mechanism Diagram](image)

Specific intermediary model as shown in formula (4) ~ (6):

\[ pm2.5_{it} = a_0 + \beta_1 gf_{it} + \beta_2 pop_{it} + \beta_3 eri_{it} + \beta_4 human + \beta_5 energyc + \epsilon_{it} \]  
\[ rdsl_{it} = a_0 + \beta_1 gf_{it} + \beta_2 pop_{it} + \beta_3 eri_{it} + \beta_4 human + \beta_5 energyc + \epsilon_{it} \]  
\[ pm2.5_{it} = a_0 + \beta_1 gf_{it} + \beta_2 rdsl_{it} + \beta_3 pop_{it} + \beta_4 eri_{it} + \beta_5 human + \beta_6 energyc + \epsilon_{it} \]  

In its formula (4)~(6), rdsl is an mediating variable, representing technological innovation; \( a_0 \) is a...
constant, $\beta_1 \sim \beta_6$ are the coefficients of the relevant influencing factors; $pop$ represents the natural population
growth rate; $human$ represents years of education per capita; $energyc$ represents the energy consumption;
$eri$ represents the local environmental regulation index and $\epsilon$ is the random error term.

3.2 Variable Description and Data Source

3.2.1 Explained variable.

The core explained variable in the regression model is PM2.5 concentration ($pm2.5$). PM2.5 is the main
component of haze, PM2.5 concentration can reflect the severity of haze to some extent. In this paper, the grid
data of global PM2.5 concentration based on satellite monitoring published by the Center for Socio-Economic
Data and Applications of Columbia University (SEDAC) were used to analyze the annual PM2.5 concentration
in China's administrative regions by ArcGIS software.

3.2.2 Core explanatory variable

This study, in connection to Yin et al. (2021) and Cui et al. (2022), develops a green finance ($gf\text{i}$) index
system that incorporates green credit, green securities, green insurance, green investment, and carbon finance
indicators. Afterwards, the system is measured using the entropy weight technique.

3.2.3 Mediating variable

Patent, as the main form of technological innovation, can be used as an indicator to evaluate technological
innovation to a large extent. Patent data is widely used as a measure of technological innovation in previous
studies (Cao et al., 2021, Cao et al., 2022). Although patent output cannot fully reflect the actual quality of
innovation activities, patent data has its unique advantages. According to Janger et al. (2017), patent indicators
may be used to measure the output of innovation, since changes in patent and innovation output are consistent
with changes in innovation factors. Hughes-Hallett (2014) finds that patents are highly correlated with
innovation, so the number of patents can be used to represent the degree of technological innovation. Number
of patent authorizations ($rdsl$) can better reflect the actual research results of technological innovation, so this
paper selects the patent acceptance number to represent the degree of technological innovation.

3.2.4 Control variable

(1) Population growth ($pop$): It refers to the natural population birth rate, which can reflect the growth of
a country's population.

(2) Financial development level ($financeim$): Following Cao et al. (2021), the level of financial
development can well measure the development of financial institutions and financial markets.

(3) Urban-rural income gap ($gap$): It refers to the difference between the disposable income of urban
residents and the disposable income of rural residents, and is one of the indicators reflecting the income
inequality of a country.

(4) Green total factor productivity ($gtp$): It is calculated based on the undesired output, using the non-
oriented SBM model-GML index to measure and calculate, which can better evaluate industrial development
and economic growth (Zhang et al., 2022).

(5) Environmental regulation ($eri$): Environmental regulation is a series of regulations formulated by
government departments for the purpose of environmental protection to reduce pollutant emissions (Shvarts
et al., 2016).

(6) Economic openness ($open$): According to Yang et al. (2021), economic openness is measured by the
share of each province's total import and export commerce in that year's GDP.

(7) Unemployment rate ($ur$): It refers to the registered unemployment rate, which can reflect the
employment level of a country's labor force (Yin et al., 2021).

(8) Years of education per capita ($human$): It refers to the average years of education of the population
over the age of six, which can reflect the overall education level of a country and reflect the overall educational
quality. 

(9) Energy consumption(\textit{energyc}): Refers to the total consumption of coal, carbon and oil (Ansari et al., 2022).

### 3.3 Descriptive statistics

The time period and countries were selected based on the availability of data, especially for our critical variables of interest. Apart from PM2.5 data, green finance index data, the relevant data for other variables were mainly obtained from China Financial Yearbook, China Environmental Statistical Yearbook, China Statistical Yearbook, China Environmental Statistics Yearbook, China Industrial Statistics Yearbook, China Insurance Yearbook, the Statistical Yearbook of each province, and Wind database. Descriptive statistics are shown in Table 1. To ensure the scientific accuracy of the empirical analysis, the relevant raw data were technically processed. In addition, the data, such as: PM2.5, Population growth, human, Energy consumption, number of patent applications were logarithmically normalized to eliminate the variable heteroscedasticity.

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### 4. Results and discussion

#### 4.1 Correlation coefficient

Before the model regression, this paper makes a simple correlation analysis of the data as a preliminary judgment. It can be seen in Table 2. There was a positive correlation between core explained variable PM2.5 concentration (pm2.5) and core explained variable green finance index (gfi), between intermediary variable number of patent applications (rdsl) and core explained variable PM2.5 (pm2.5), between intermediary variable number of patent applications (rdsl) and core explained variable green finance index (gfi). The coefficients were 0.174, 0.406 and 0.588, respectively. A preliminary observation of the correlation coefficient table shows that there is a positive correlation between population growth (\textit{pop}), economic openness (\textit{open}), years of education per capita (\textit{human}), energy consumption (\textit{energyc}) and PM2.5; Financial development level (\textit{financeim}), Urban-rural income gap (\textit{gap}), the Green total factor productivity(\textit{gtfp}), Unemployment rate(\textit{ur}) are negatively correlated with PM2.5. This result will only provide a preliminary judgment for this study.
4.2 OLS panel regression and Spatial regression

4.2.1 Space dependence test

Before constructing the spatial model, we solve the global Moran index of pm2.5 and gfi from 2011 to 2019 based on formula (2). The spatial matrix is selected as the geographical distance matrix, and the results are shown in Table 3. From Table 3, it can be seen that from 2011 to 2019, the Moran index of pm2.5 was significantly indigenous at the level of 1%, and the Moran index of gfi was significantly indigenous at the level of 5% in 2018, and all of them were substantially indigenous at 1%, indicating a severe spatial autocorrelation. Therefore, it is reasonable to construct a spatial model for research.

Table 3
Moran I test results.

<table>
<thead>
<tr>
<th>Year</th>
<th>pm2.5</th>
<th>gfi</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>0.238***</td>
<td>0.027***</td>
</tr>
<tr>
<td></td>
<td>(0.092)</td>
<td>(0.081)</td>
</tr>
<tr>
<td>2012</td>
<td>0.212***</td>
<td>0.223***</td>
</tr>
<tr>
<td></td>
<td>(0.090)</td>
<td>(0.081)</td>
</tr>
<tr>
<td>2013</td>
<td>0.235***</td>
<td>0.219***</td>
</tr>
<tr>
<td></td>
<td>(0.093)</td>
<td>(0.080)</td>
</tr>
<tr>
<td>2014</td>
<td>0.288***</td>
<td>0.223***</td>
</tr>
<tr>
<td></td>
<td>(0.092)</td>
<td>(0.078)</td>
</tr>
<tr>
<td>2015</td>
<td>0.276***</td>
<td>0.204***</td>
</tr>
<tr>
<td></td>
<td>(0.093)</td>
<td>(0.078)</td>
</tr>
<tr>
<td>2016</td>
<td>0.266***</td>
<td>0.175***</td>
</tr>
<tr>
<td></td>
<td>(0.093)</td>
<td>(0.075)</td>
</tr>
<tr>
<td>2017</td>
<td>0.254***</td>
<td>0.146***</td>
</tr>
</tbody>
</table>
Additionally, by displaying the regional Moran’s I scatter plots of the key variables in 2019, we may investigate the instability and the kind of local spatial agglomeration (Cao, et al., 2022). The coordinates of Moran’s I scatter plots are \(\left[ x_i - \bar{x}, W(x_i - \bar{x}) \right] \). \(W\) is the geographical distance spatial weight matrix. The four quadrants in the scatter plot are used to identify the positive spatial autocorrelation (High-High and Low-Low) of the fitting line in the first and third quadrants, respectively, indicating that the green finance and PM2.5 in the region change in the same direction as their surrounding areas; The fitting lines in the second and fourth quadrants represent negative spatial autocorrelation (High-Low and Low-High), indicating that the change direction of green finance and PM2.5 in the region is opposite to that in the surrounding areas. By observing Fig. 3, the Moran scatter plot (3a) of pm2.5 in 2019 shows that 12 provinces (40%) fall in the first quadrant and 10 provinces (33.33%) fall in the third quadrant, belonging to H-H and L-L clustering, which proves that pm2.5 has positive spatial autocorrelation. By observing the Moran scatter plot (3b) of gfi in 2019, it can be seen that 5 provinces fall in the first quadrant (16.7%) and 19 provinces (63.33%) fall in the third quadrant, belonging to H-H and L-L clustering, which proves that gfi also has positive spatial autocorrelation.

4.2.2 Discussion on OLS panel regression result and spatial regression results

Additionally, by displaying the regional Moran's I scatter plots of the key variables in 2019, we may investigate the instability and the kind of local spatial agglomeration. The results are shown in Model (1) in Table 4. As can be seen from Model (1a) (ols), green finance (gfi) has a significantly negative correlation with PM2.5 (pm2.5) at the 1 % level, and the coefficient is \(-1.251\), that is, green finance has a strong inhibitory effect on PM2.5 emissions. Green finance can provide financial support to emerging green enterprises through green credit and green bonds, on the one hand, and can also support green transformation and upgrading of
traditional enterprises to reduce emissions of pollutants, such as PM2.5 (Nassiry, D., 2018). Therefore, hypothesis one is proved. At the same time, we also see that the impact of population growth \((\text{pop})\) on PM2.5 is positive at a 10% level. This result is similar to the research results of most scholars, who agree that the increase in population is one of the key factors affecting resource consumption and environmental pollution, and there is a positive correlation between them (Nasrollahi et al., (2020), Jahanger et al., (2021), Hao et al., (2020)). The large population and “high population operation” are the main reasons for resource consumption and environmental pollution in China. There is a significant positive correlation between urban-rural income gap and PM2.5 at 1% level, and the coefficient is 0.085. As we all know, China’s urban-rural income gap is relatively large and uneven, which will lead to the transfer of labor from rural to urban, labor from agriculture to industry. Due to the low level of education, most of these labors can only flow to labor-intensive and energy-intensive traditional sectors (Cui et al., 2022). Therefore, the production scale of the traditional sector will expand, which will increase PM2.5 emissions. Environmental regulation \((\text{eri})\) and PM2.5 at 1% level has a significant positive correlation coefficient of 0.053. That is to say, environmental regulation will promote PM2.5 emissions. Many scholars also believe that environmental regulation cannot effectively reduce environmental pollution (Cao et al., 2022). For example, Sinn (2008) proposed the “green paradox”. He believed that environmental regulation cannot reduce pollutant emissions, but will reduce the empirical efficiency of enterprises, which is not conducive to the improvement of environmental problems. Cai et al., (2020); Zeng et al. (2022) and Zhang et al., (2021) have come to a similar conclusion that strict environmental regulation has a significant inhibitory effect on business operation and a positive promotion relationship on pollution emissions. By comparing the results of Model (1a) (ols) and Model (1b) (2sls), it can be seen that the correlation and visibility of each variable have not changed greatly. Moreover, the two models have good goodness of fit \((R^2)\), which are 0.979 and 0.982, respectively, so the results have strong robustness.

As mentioned above, PM2.5 has a strong spatial correlation, so it is necessary to carry out the regression of the spatial model. The regression results are shown in Model (2) in Table 4. In Model (2a) (Main) and Model (2b) (Wx), we find that the positive and negative coefficients of the main regression variables are basically consistent with the OLS regression results, but there are differences in the numerical value and the degree of dominance, which further illustrates the necessity of studying the spatial effect. Based on the geographical distance spatial weight matrix and spatial Durbin model, this paper studies the impact of green finance on PM2.5 emissions. As shown in Table 4 Model (2), hausman test passes the 1% level of visibility test, so the fixed effect model is selected. Log-likelihood (LR) test found that the spatial and temporal fixed effects are obvious. The Wald test and LR test of Spatial lag model (SLM) and spatial error model (SEM) model passed the 1% level of significance test, which rejected the original assumption that SDM model can be simplified as SLM or SEM, and proved that the spatial Durbin model is reasonable. In order to further prove the rationality of using the spatial Durbin model, this paper also conducted the Lagrange multiplier test (LM test), and the results are shown in Table 5. The results also show that the SDM model cannot be degenerated into SLM or SEM model, so the spatial Durbin model is selected in this paper.

Through Model (2a) (Main) and Model (2b) (Wx), it can be seen that the direct effect of green finance on PM2.5 is negatively correlated at 1% level with a coefficient of -1.115. The spatial spillover effect is significantly negative at the level of 5%, and the coefficient is −0.901, which proves that the green financial development of the province not only has a significant inhibitory effect on the PM2.5 emissions of the province, but also has a significant inhibitory effect on the PM2.5 emissions of other provinces in space. This is because green finance can provide financial support to the province and other provinces, bringing green upgrading of industrial structure and efficient utilization of resources, in order to reduce PM2.5 emissions. At the same time, green finance is conducive to the gradual improvement of regional economic integration and the formation of
industrial chain (Lee et al., 2020). As a result, green finance has promoted the green upgrading of the whole regional industry, formed a new pattern of mutual influence and mutual promotion, and reduced PM2.5 emissions in the spatial effect. It can also be seen that the direct effects of population growth ($pop$) and financial development level ($financeim$) on pm2.5 are positive at the 10 per cent level with coefficients of 0.421 and 0.022, respectively; The spatial spillover effect was positive at 5% level, and the coefficients were 1.249 and 0.054. It proves that the population growth rate and financial development level of the province will have a significant and indigenous promoting effect on the PM2.5 emissions of the province, and the promoting effect in space is stronger, that is, the promoting effect of the population growth and financial development level of the province on the PM2.5 emissions of the other province is stronger. Population has strong liquidity, and with the transformation of China’s economic development and the green upgrading of industrial structure, the degree of population inter-provincial mobility is also increasing. Therefore, part of the labor force in the province will flow into other provinces under the pressure of green development policy, providing labor for high-pollution industries in provinces with low environmental regulation threshold, which increases the production output of other provinces and promotes the PM2.5 emission of other provinces (Yu et al., 2021). The level of financial development ($financeim$) has a significant promoting effect on the direct effect and spatial spillover effect of PM2.5, which are significant at the levels of 10% and 5% respectively, with coefficients of 0.002 and 0.054. The level of financial development is mainly reflected in the degree of development of financial institutions (Yin et al., 2022). Developed financial institutions can improve the efficiency of capital use in the surrounding areas and increase social aggregate supply, while the short-term production structure is difficult to change, so expanding production in the original production technology will increase PM2.5 emissions. Therefore, the promoting effect of financial development level on PM2.5 emissions of neighboring provinces is higher than that of the province.

### Table 4

<table>
<thead>
<tr>
<th></th>
<th>OLS (Fixed effects)</th>
<th>Spatial Durbin (Fixed effects)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model (1a) (ols)</td>
<td>Model (1b) (2sls)</td>
</tr>
<tr>
<td>gfi</td>
<td>-1.251***</td>
<td>-1.930 ***</td>
</tr>
<tr>
<td></td>
<td>(0.281)</td>
<td>(0.500)</td>
</tr>
<tr>
<td>pop</td>
<td>0.470*</td>
<td>0.635**</td>
</tr>
<tr>
<td></td>
<td>(0.271)</td>
<td>(0.303)</td>
</tr>
<tr>
<td>financeim</td>
<td>0.022</td>
<td>-0.003</td>
</tr>
<tr>
<td></td>
<td>(0.014)</td>
<td>(0.016)</td>
</tr>
<tr>
<td>gap</td>
<td>0.085***</td>
<td>0.187**</td>
</tr>
<tr>
<td></td>
<td>(0.025)</td>
<td>(0.095)</td>
</tr>
<tr>
<td>gtfp</td>
<td>-0.007</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>(0.013)</td>
<td>(0.012)</td>
</tr>
<tr>
<td>eri</td>
<td>0.053***</td>
<td>0.040*</td>
</tr>
<tr>
<td></td>
<td>(0.202)</td>
<td>(0.023)</td>
</tr>
<tr>
<td>_cons</td>
<td>1.270</td>
<td>-0.196</td>
</tr>
<tr>
<td></td>
<td>(1.928)</td>
<td>(2.280)</td>
</tr>
<tr>
<td>Hausman(p-value)</td>
<td>0.000</td>
<td>LR_time</td>
</tr>
</tbody>
</table>
The direct effect is numerically equal to the sum of the spatial Durbin model coefficient and the feedback effect coefficient. Specifically, the feedback effect refers to that the explanatory variable (green finance) of a certain region will affect the explained variable (PM2.5) of its neighboring region, and in turn will affect the explained variable (PM2.5) of the region. Indirect effects are used to measure the impact of an explanatory variable (green finance) in the surrounding region on the explained variable in the region (PM2.5). Through partial differential decomposition, the decomposition of spatial effect into direct effect and indirect effect can reduce the error and analyze the spatial spillover effect more accurately.

As shown in Model (3a) in Table 6, Direct, Indirect and Total represent the direct, indirect and total effects of green finance on PM2.5. The direct and indirect effects of green finance on PM2.5 were significant at the 1% level, and the coefficients were -1.324 and -3.572, respectively. Facts have proved that green finance not only has a significant inhibitory effect on PM2.5 emissions in the province, but also its negative spatial spillover effect will gradually increase with the expansion of geographical distance. The development of green finance in this province can promote the development of green finance in surrounding provinces, especially in economically developed areas, which will lead to the development of underdeveloped areas around the 'radiation effect' (Lc et al., 2021). The provinces with developed green finance generally pay more attention to
The emission control of pollutants and the protection of the environment. Therefore, the indirect inhibitory effect of the development of green finance on PM2.5 emissions in surrounding provinces is greater than the direct effect of green finance in this province. At the same time, it can be observed that the direct effect, indirect effect and total effect of population growth rate, financial development level and urban-rural income gap have a significant role in promoting PM2.5 emissions, but the degree and coefficient are different, which proves that population growth rate, financial development level and urban-rural income gap will promote PM2.5 emissions to a certain extent (Chen et al., 2021; Dong et al., 2018).

### Table 6
Decomposition of spatial effects based on national sample.

<table>
<thead>
<tr>
<th>Model</th>
<th>Model (3a)</th>
<th>Model (3b)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Direct</td>
<td>Indirect</td>
</tr>
<tr>
<td>gfi</td>
<td>-1.324***</td>
<td>-3.572***</td>
</tr>
<tr>
<td></td>
<td>(0.238)</td>
<td>(1.262)</td>
</tr>
<tr>
<td>pop</td>
<td>0.062**</td>
<td>3.443**</td>
</tr>
<tr>
<td></td>
<td>(0.253)</td>
<td>(1.437)</td>
</tr>
<tr>
<td>financeim</td>
<td>0.033***</td>
<td>0.159**</td>
</tr>
<tr>
<td></td>
<td>(0.013)</td>
<td>(0.063)</td>
</tr>
<tr>
<td>gap</td>
<td>0.072***</td>
<td>0.246**</td>
</tr>
<tr>
<td></td>
<td>(0.024)</td>
<td>(0.118)</td>
</tr>
<tr>
<td>gtpf</td>
<td>-0.003</td>
<td>0.056</td>
</tr>
<tr>
<td></td>
<td>(0.012)</td>
<td>(0.054)</td>
</tr>
<tr>
<td>eri</td>
<td>0.055**</td>
<td>-0.010***</td>
</tr>
<tr>
<td></td>
<td>(0.023)</td>
<td>(0.152)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Obs</th>
<th>270</th>
</tr>
</thead>
<tbody>
<tr>
<td>Province</td>
<td>30</td>
</tr>
</tbody>
</table>

Standard errors in parentheses: * p<0.1, ** p<0.05, *** p<0.01.

### 4.2.3 Discussion on robustness test result

This research uses two ways to assess the empirical model's robustness. First, replace spatial regression's distance weight matrix with a 0-1 adjacent weight matrix. The results are shown in Table 6 Model (3b). The results show that the regression results are basically consistent with the spatial geographic distance weight matrix regression results Model (3a), and the empirical results are robust. The second is to test whether the empirical results will happen by gradually increasing the control variables based on the original control variables. This paper gradually adds two variables, Economic openness (open) and Unemployment rate (ur), to test the robustness of the model. The test results are shown in Table 7, which are basically consistent with the results of the previous spatial regression. It can also prove that the empirical results obtained by the spatial model used in this paper are robust.

### Table 7
Stepwise increase of control variables for spatial regression robustness test

| open | open ur |
What role does technological innovation play in the impact of green finance on PM2.5 emissions? What kind of influence mechanism is it? This paper constructs a mediating effect model to explore. Before the beginning of the mediation effect model regression, Bootstrap and Sobel test are carried out, and the test results are shown in table 8. The Bootstrap test results show that the indirect effect (_bs_1) and direct effect (_bs_2) of green finance on PM2.5 emissions are significant at 1% confidence level, and the coefficients are -0.625 and -0.973, that is, green finance has a significant inhibitory effect on PM2.5 emissions. The results of Sobel test were also significant at 1% confidence level, and the coefficient was -0.625, which proved the effectiveness of the mediating effect.

**Table 8**
Bootstrap and Sobel test

<table>
<thead>
<tr>
<th></th>
<th>MAIN</th>
<th>WX</th>
<th>Direct</th>
<th>Indirect</th>
<th>Total</th>
<th>MAIN</th>
<th>WX</th>
<th>Direct</th>
<th>Indirect</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>gfi</td>
<td>-1.330***</td>
<td>-0.947**</td>
<td>-1.546***</td>
<td>-3.710***</td>
<td>-5.256***</td>
<td>-1.340***</td>
<td>-0.957**</td>
<td>-1.560***</td>
<td>-3.770***</td>
<td>-5.330***</td>
</tr>
<tr>
<td></td>
<td>(0.215)</td>
<td>(0.422)</td>
<td>(0.234)</td>
<td>(1.186)</td>
<td>(1.289)</td>
<td>(0.215)</td>
<td>(0.430)</td>
<td>(0.240)</td>
<td>(1.322)</td>
<td>(1.433)</td>
</tr>
<tr>
<td>pop</td>
<td>0.393</td>
<td>1.973***</td>
<td>0.647***</td>
<td>4.863***</td>
<td>5.537**</td>
<td>0.389</td>
<td>2.014***</td>
<td>0.683***</td>
<td>5.055***</td>
<td>5.739***</td>
</tr>
<tr>
<td></td>
<td>(0.252)</td>
<td>(0.627)</td>
<td>(0.248)</td>
<td>(1.470)</td>
<td>(1.548)</td>
<td>(0.254)</td>
<td>(0.638)</td>
<td>(0.257)</td>
<td>(1.626)</td>
<td>(1.724)</td>
</tr>
<tr>
<td>financeim</td>
<td>0.027**</td>
<td>0.080***</td>
<td>0.041***</td>
<td>0.211***</td>
<td>0.252***</td>
<td>0.027**</td>
<td>0.078***</td>
<td>0.041***</td>
<td>0.208***</td>
<td>0.249***</td>
</tr>
<tr>
<td></td>
<td>(0.013)</td>
<td>(0.027)</td>
<td>(0.013)</td>
<td>(0.068)</td>
<td>(0.075)</td>
<td>(0.013)</td>
<td>(0.030)</td>
<td>(0.014)</td>
<td>(0.072)</td>
<td>(0.080)</td>
</tr>
<tr>
<td>gap</td>
<td>0.020</td>
<td>0.014</td>
<td>0.024</td>
<td>0.058</td>
<td>0.082</td>
<td>0.020</td>
<td>0.013</td>
<td>0.023</td>
<td>0.053</td>
<td>0.076</td>
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<tr>
<td></td>
<td>(0.023)</td>
<td>(0.051)</td>
<td>(0.027)</td>
<td>(0.114)</td>
<td>(0.129)</td>
<td>(0.024)</td>
<td>(0.052)</td>
<td>(0.027)</td>
<td>(0.123)</td>
<td>(0.137)</td>
</tr>
<tr>
<td>gtfp</td>
<td>-0.000</td>
<td>0.040*</td>
<td>0.005</td>
<td>0.091*</td>
<td>0.096</td>
<td>-0.000</td>
<td>0.039*</td>
<td>0.005</td>
<td>0.086</td>
<td>0.091</td>
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<tr>
<td></td>
<td>(0.012)</td>
<td>(0.024)</td>
<td>(0.012)</td>
<td>(0.055)</td>
<td>(0.059)</td>
<td>(0.012)</td>
<td>(0.024)</td>
<td>(0.012)</td>
<td>(0.058)</td>
<td>(0.063)</td>
</tr>
<tr>
<td>eri</td>
<td>0.054***</td>
<td>-0.151**</td>
<td>0.039*</td>
<td>-0.266*</td>
<td>-0.227</td>
<td>0.055***</td>
<td>-0.148**</td>
<td>0.041*</td>
<td>-0.248</td>
<td>-0.207</td>
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<tr>
<td></td>
<td>(0.020)</td>
<td>(0.008)</td>
<td>0.023</td>
<td>0.152</td>
<td>0.166</td>
<td>(0.020)</td>
<td>(0.066)</td>
<td>0.023</td>
<td>0.157</td>
<td>0.168</td>
</tr>
<tr>
<td>open</td>
<td>-0.197***</td>
<td>-0.369**</td>
<td>-0.260***</td>
<td>-1.039***</td>
<td>-1.300***</td>
<td>-0.203***</td>
<td>-0.364**</td>
<td>-0.264***</td>
<td>-1.055**</td>
<td>-1.319***</td>
</tr>
<tr>
<td></td>
<td>(0.062)</td>
<td>(0.173)</td>
<td>(0.071)</td>
<td>(0.429)</td>
<td>(0.471)</td>
<td>(0.063)</td>
<td>(0.174)</td>
<td>(0.072)</td>
<td>(0.451)</td>
<td>(0.492)</td>
</tr>
<tr>
<td>ur</td>
<td>0.000</td>
<td>0.014</td>
<td>0.002</td>
<td>0.034</td>
<td>0.035</td>
<td>(0.013)</td>
<td>(0.041)</td>
<td>(0.167)</td>
<td>(0.101)</td>
<td>(0.112)</td>
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<td>rho</td>
<td>0.557***</td>
<td>0.557***</td>
<td>(0.078)</td>
<td>(0.079)</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>sigma2_e</td>
<td>0.002***</td>
<td>0.002***</td>
<td>(0.000)</td>
<td>(0.000)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Standard errors in parentheses:  * p<0.1, ** p<0.05, *** p<0.01.

4.3 Discussion on mediating effect regression result

What role does technological innovation play in the impact of green finance on PM2.5 emissions? What kind of influence mechanism is it? This paper constructs a mediating effect model to explore. Before the beginning of the mediation effect model regression, Bootstrap and Sobel test are carried out, and the test results are shown in table 8. The Bootstrap test results show that the indirect effect (_bs_1) and direct effect (_bs_2) of green finance on PM2.5 emissions are significant at 1% confidence level, and the coefficients are -0.625 and -0.973, that is, green finance has a significant inhibitory effect on PM2.5 emissions. The results of Sobel test were also significant at 1% confidence level, and the coefficient was -0.625, which proved the effectiveness of the mediating effect.
soble -0.625***
(0.187)

Goodman-1 (Aroian) -0.625***
(0.188)

Goodman-2 -0.625***
(0.187)

Standard errors in parentheses: * p<0.1, ** p<0.05, *** p<0.01.

As shown in Table 9, in Path (1), the impact of green finance on PM2.5 emissions is significantly negative at the level of 1%, and the coefficient is −1.598, indicating that green finance has a significant inhibitory effect on PM2.5 emissions. Path (2)'s indirect regression findings demonstrate that green funding has a considerable positive influence on technological innovation at the 1% level, with a coefficient of 6.296. Therefore, Hypothesis 2 is verified. It can be seen from Path (3) that the impact of technological innovation on PM2.5 shows a significant negative effect at the level of 1%, with a coefficient of -0.1, that is, the development of technological innovation will inhibit the emission of PM2.5. Therefore, Hypothesis 3 is verified. At the same time, it can be seen from Table 9 that the inhibitory effect of green finance on PM2.5 is more obvious in the total effect Path (1) than in the direct effect Path (3), and its coefficients are −1.598 and −0.973. The empirical results show that green finance will promote the progress of technological innovation, and the improvement of technology will reduce PM2.5 emissions. Green financial instruments can reduce the financing constraints of enterprises by reasonably matching risks and benefits, so as to increase the source of funds for R&D activities with greater risks and ensure the development of technological innovation activities of R&D enterprises (Wang et al., 2020; Cao et al.2022). At the same time, technological innovation can achieve balanced development between economic growth and environmental protection by reducing environmental pollution and promoting new technologies and services for sustainable development. It can help enterprises achieve a win-win situation of economic and environmental benefits, and is an important way to reduce the adverse impact of economic activities on the environment (Yu et al., 2022). At present, technological innovation related to the upgrading of industrial structure and energy structure is one of the main types of innovation, aiming at improving production efficiency, reducing traditional energy consumption and reducing pollutant emissions (Song et al., 2020). Therefore, the vigorous development of technological innovation is conducive to inhibiting PM2.5 emissions.

In addition, we can learn from table 9 that the population growth rate (pop) has a positive effect on PM2.5 emissions and technological innovation at a 1% level, which means that higher population growth rates will increase PM2.5 emissions and promote technological innovation (Dong et al., 2019). It is not difficult to understand that the increase in population will lead to an increase in the total demand of the whole society, thereby promoting total social production. In the short term, the production mode will not change greatly, and the increase of total output will increase energy consumption, so PM2.5 emissions will also increase. Due to the increase in population, the old production mode cannot adapt to the expanded production demand. Through technological innovation, new production modes with high efficiency and low consumption can be generated, so as to reduce PM2.5 emissions. Energy consumption (energy) is significantly positive for PM2.5 emissions and technological innovation at the 1% confidence level, because the formation of PM2.5 is mainly caused by energy consumption, so the increase in energy consumption will increase PM2.5 emissions (Yan et al., 2018). As the increasing energy consumption will lead to less and less non-renewable energy left. In order to achieve sustainable development, it is necessary to improve the efficiency of energy use and shift to the research and
development of new clean energy through technical improvement (Hepburn et al., 2021). However, in terms of the total effect, energy consumption will still promote the emission of PM2.5.

Table 9

Results of mediating effect regression analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Path (1)</th>
<th>Path (2)</th>
<th>Path (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pm2.5</td>
<td></td>
<td></td>
<td>-0.100***</td>
</tr>
<tr>
<td>rdsl</td>
<td>-</td>
<td>-</td>
<td>(0.029)</td>
</tr>
<tr>
<td>gfi</td>
<td>-1.598***</td>
<td>6.296***</td>
<td>-0.973***</td>
</tr>
<tr>
<td></td>
<td>(0.231)</td>
<td>(0.483)</td>
<td>(0.290)</td>
</tr>
<tr>
<td>pop</td>
<td>0.171***</td>
<td>0.448***</td>
<td>0.216***</td>
</tr>
<tr>
<td></td>
<td>(0.017)</td>
<td>(0.035)</td>
<td>(0.021)</td>
</tr>
<tr>
<td>eri</td>
<td>0.042</td>
<td>-0.689***</td>
<td>-0.026</td>
</tr>
<tr>
<td></td>
<td>(0.050)</td>
<td>(0.104)</td>
<td>(0.053)</td>
</tr>
<tr>
<td>human</td>
<td>1.615***</td>
<td>-3.771***</td>
<td>1.024***</td>
</tr>
<tr>
<td></td>
<td>(0.264)</td>
<td>(0.554)</td>
<td>(0.281)</td>
</tr>
<tr>
<td>energyc</td>
<td>0.149***</td>
<td>1.590***</td>
<td>0.307***</td>
</tr>
<tr>
<td></td>
<td>(0.041)</td>
<td>(0.087)</td>
<td>(0.061)</td>
</tr>
<tr>
<td>_cons</td>
<td>-2.015***</td>
<td>0.727</td>
<td>-1.942***</td>
</tr>
<tr>
<td></td>
<td>(0.624)</td>
<td>(1.307)</td>
<td>(0.612)</td>
</tr>
</tbody>
</table>

Standard errors in parentheses: * p<0.1, ** p<0.05, *** p<0.01.

5. Conclusion

This research analyzed panel data in 30 Chinese provinces from 2011 to 2019 to examine green finance and technological innovation's influence on PM2.5 emissions. Due to the strong spatial correlation in the development of green finance, technological innovation and PM2.5, so it is more in line with the actual situation of China to do the relative study from a spatial perspective. This study is of great significance for promoting the coordinated development of haze control in China. The results show that: First, green finance can significantly inhibit the PM2.5 emission of the local province, but it has a stronger inhibition effect on the PM2.5 of surrounding provinces. Second, green finance has a significant promoting effect on technological innovation. Third, technological innovation can significantly realize the reduction of PM2.5 emissions by improving production efficiency and providing new production methods. Based on the above conclusions, this paper puts forward the following recommendations:

First, vigorously developing green finance can significantly reduce PM2.5 emissions. Green finance takes financial institutions as the main body, enterprises and the public as the main participants, and guides funds to enterprises that meet the green financial support standards, so as to promote the green development of society, and the transformation of industrial structure and energy structure to reduce PM2.5 emissions. First, how to efficiently identify which enterprises meet the green financial support standards plays a vital role in the rapid, efficient and accurate flow of funds into these enterprises. Solving the information asymmetry can make the demanders and suppliers of green funds match each other, avoid the idle of green funds or the waste of resources caused by the flow of green funds to non-green standard enterprises. Secondly, resources are limited, so green enterprises should take active policies to vigorously develop green products so that fund providers can find and choose high-quality green products and enterprises for support. Thirdly, we should speed up the
infrastructure construction related to green finance and optimize the development ecology of green finance. It is also conducive to the long-term sustainable development of green finance to establish a sharing platform based on the records of corporate pollution and environmental violations and a sound green credit system as an important part of the whole social credit system. Finally, since the development of green finance has spatial linkage and diffusion effect, it can better promote green finance in surrounding areas. Therefore, it is necessary to increase the empty cooperation of green finance among various regions, so that the developed regions of green finance can drive the development of the surrounding underdeveloped regions, and make the green finance in the underdeveloped regions develop rapidly, so as to better suppress the emission of PM2.5.

Second, green finance can improve the ability of technological innovation enterprises to innovate. Green finance prioritizes environmental-related technologies as an important mechanism to alleviate haze pollution and reduce PM2.5 emissions. As an incentive and control tool, green finance can alleviate haze pollution. From the perspective of incentive, the government can broaden the green financing channels of enterprises, increase subsidies for qualified green projects, and make enterprises have enough funds for ecological innovation. From the perspective of control, the government can establish a set of evaluation mechanism on the effect of green financial policy as soon as possible to provide green financial support for enterprises. At the same time, the government should also strengthen the disclosure standards of enterprise environmental information. On the one hand, more attention should be paid to the regulation of innovative technologies to reduce PM2.5 emissions to reduce haze pollution. On the other hand, when formulating green finance policies, the government should fully consider the heterogeneity of enterprises and avoid taking 'one size fits all' approach. Differentiated green financial policies can truly achieve win-win, improve the quality of enterprise innovation, control haze pollution and reduce PM2.5 emissions. For state-owned enterprises, the government should specialize in funds, improve their social responsibility for environmental governance, and raise the threshold for state-owned enterprises to obtain green financial support, so as to improve the efficiency of green funds in promoting technological innovation. In addition, the government should further improve the enterprise qualification audit mechanism and provide more convenient green financial support to enterprises, so as to increase the investment of enterprises in technological innovation and improve the technological innovation ability of enterprises.

Third, due to China’s energy endowment of “rich coal and less oil” and the current situation of coal-fired heating in the northern region, it is not realistic to change the direction of energy production and energy consumption structure in the short term. Therefore, in the short term, it can promote the development of technological innovation and improve energy utilization, limit the inflow and use of inferior coal, and expand the use range of high-quality coal. Increasing investment in environmental governance in areas with high PM2.5 emissions, accelerating the conversion of new kinetic energy and on kinetic energy, breaking the 'lock-in effect' of economic development relying on energy consumption. At the same time in these areas to establish ecological damage compensation mechanism, with environmental protection systems and regulations, forcing local enterprises to enhance technology and innovation activities. Technological innovation drives energy system reform to reduce PM2.5 emissions. The state controls the direction of green development in the top-level design, coordinates the convergence of industry-university-research cooperation, stimulates the enthusiasm of green technology use in the industry and major energy enterprises, realizes the multi-channel combination of key technologies and core technologies, improves the clean and efficient utilization level of traditional energy such as coal, and develops clean energy distributedly. Providing cleaner and cheaper energy products through technological advances provides strong energy and technological support for reducing PM2.5 emissions. And in the research and development stage to keep up with the pace of development, pay attention to pollution rebound effect, reduce the technology transformation stage of green environmental protection
standard shrinkage behavior. The impacts of technological innovation at different stages on reducing PM2.5 emissions are different. The environmental problems brought about by the economic development and industrial structure in the technology research and development stage are reflected in the technology transformation stage. By controlling the preference of technology development from the source of technology development, it can make up for the lack of energy-saving technologies produced in the technology transformation stage, to adapt to the energy rebound effect brought about by new technologies.

However, this study only examines Chinese research samples, while the research on international related topics needs to be further expanded. In addition, the spatial research model adopted in this paper does not consider the threshold effect, but some studies show that the spatial regression results have the threshold effect of spatial distance. Therefore, the use of more accurate regression models will improve the reference value of this study.

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**Authors Contributions**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Yiniu Cui], [Desheng Wu], [Cheng Zhong] and [Jianhong Cao]. The first draft of the manuscript was written by [Yiniu Cui] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Not applicable.

**Consent for publication**

Not applicable.

**Consent to Participate**

Not applicable.

**Competing interests**

The authors declare that no competing interests.

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