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An Empirical Study on the Impact Mechanism of PM2.5 on the Credit Spread of Green Bonds in China

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ABSTRACT
This study investigates the impact mechanism of PM2.5 concentration on the credit spread of green bonds, using a sample of 2,094 green bonds issued in China from 2016 to 2023. It comprehensively employs the two-way fixed effects model, mediation effect model, and instrumental variable method. The research fills the gap in understanding how micro-pollutants (PM2.5) affect green bond pricing. It empirically verifies the direct positive impact of PM2.5 on green bond spreads, as well as the mediating transmission mechanisms of third-party certification and regional public opinion attention in the relationship between them. This study provides evidence from the Chinese market for the integration of environmental risks into the green financial asset pricing system.

KEYWORDS
PM2.5; Green bonds; Credit spreads; Mediation effect model; Environmental risk

1 Research background and significance

1.1 Research background

In recent years, China's green bond market has developed rapidly and has become an important financial instrument to support the "dual carbon" goals. However, the mechanism by which external environmental factors influence market pricing remains unclear. Meanwhile, as a typical micro air pollutant, PM2.5's potential impact on financial market risk preferences and asset pricing has gradually attracted attention. Nevertheless, existing studies have not systematically clarified its correlation path with green bond spreads.

1.2 Research significance

1.2.1 Theoretical significance

It makes up for the limitation that existing studies mostly focus on macro-environmental factors while ignoring the micro-level impact of PM2.5, enriches the theoretical framework in the field of "environmental risk-green financial pricing", and improves the application of mediation effect in interdisciplinary research on environmental finance.

1.2.2 Practical significance

It provides a basis for financial institutions to incorporate PM2.5 into the green bond risk pricing system, and also offers references for policymakers to optimize the supervision of the green financial market and balance the financing costs of different regions and entities.

2 Review of domestic and foreign literature

Against the backdrop of the global advancement of the "dual carbon" goals and the deepening of environmental pollution prevention and control, green bonds, as a core financial instrument connecting environmental protection needs and capital allocation, have seen increasingly important research on their market pricing mechanisms and the correlation with external influencing factors. Air pollution, as a typical environmental externality variable, not only changes investors' risk preferences through physical health and emotional fluctuations but also is likely to have complex impacts on green bond pricing through paths such as the information environment and public cognition. Existing studies have explored the "emotional effect" of air pollution on the financial market and the "green premium" characteristics of green assets. However, there is still a gap in the systematic analysis of how PM2.5 affects green bond spreads through three paths: direct impact, intermediary transmission (third-party certification), and external public opinion.

From the perspective of the correlation between air pollution and green bond spreads, the influencing factors of green bond spreads are widely placed under the theoretical framework of "green premium". Existing studies have confirmed that green bonds, due to their clear allocation of funds to environmental protection projects, often have a negative

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premium compared to conventional bonds [1-2]. Lyu et al [3]. found that the higher the carbon emission reduction benefit of green bonds, the larger the "green premium" range. Zhou & Zhou [4] verified that green attributes reduce credit spreads by enhancing investor recognition. However, when air pollution is introduced, the pricing logic may change: Guo & Zhang, Chen et al. [5-6]pointed out that the increase in PM2.5 concentration will push up the risk pricing of conventional stocks through the "emotional effect". Gao et al. [7] and Liu et al. [8] believe that air pollution may enhance investors' environmental protection preferences and increase the demand for green assets, but existing studies have not clarified the specific correlation direction between PM2.5 and green bond spreads. Based on the risk pricing theory, the increase in regional PM2.5 intensity will increase the uncertainty of environmental protection projects and reduce investors' trust in environmental performance. Combined with the conclusion of Li & Peng [9] that "air pollution intensifies investors' risk aversion to assets in polluted areas", Hypothesis 1 is proposed: There is a positive correlation between the increase in regional PM2.5 intensity and the local green bond spread, that is, the higher the PM2.5 concentration, the larger the green bond spread.

From the perspective of the intermediary role of third-party certification, third-party certification is a core mechanism to alleviate information asymmetry in the green bond market and prevent "greenwashing" [10]. Existing studies have confirmed that it can reduce credit spreads through authoritative endorsement [11-12], but the impact of air pollution on the implementation probability of third-party certification has not been explored. Issuers in areas with high PM2.5 may reduce certification applications due to concerns about project defects being exposed and increased certification costs, and certification institutions may also be stricter in reviewing projects in highly polluted areas. Combined with the conclusions of El Ouadghiri et al. [13] that "the lack of third-party certification intensifies information asymmetry" and He & Liu [14] that "the public in highly polluted areas have lower tolerance for 'greenwashing'", Hypothesis 2 is proposed: PM2.5 intensity can increase green bond credit spreads by reducing the probability of third-party certification of green bonds.

From the perspective of the linkage between PM2.5 and regional public opinion index, the stimulating effect of air pollution on public attention has become a hot topic in cross-disciplinary research. Li et al. [15] found that the concentration of PM2.5 is significantly positively correlated with the search volume of "air pollution" keywords. Bickerstaff & Walker [16] pointed out that high PM2.5 will prompt the public to pay attention to environmental issues through the Internet and media; Wang & Zhao [17], El Ouadghiri et al. [13] verified that the increase in public environmental attention will affect the demand for green assets, but existing studies have not clarified how PM2.5 forms public opinion related to green bonds through public attention. Based on the "limited attention theory", PM2.5, as an intuitive environmental stressor, will occupy public attention first. Combined with the conclusion of Wu et al. [18] that "air pollution triggers collective environmental appeals through online platforms", Hypothesis 3 is proposed: PM2.5 intensity can increase green bond credit spreads by promoting the regional public opinion index.

Comprehensively, existing studies have three core gaps: the specific correlation direction between PM2.5 and green bond spreads is not clear, the intermediary role of third-party certification is ignored, and the linkage research between PM2.5 and the public opinion index related to green bonds is insufficient. The three hypotheses proposed in this study form a complete analysis system of "direct effect - intermediary effect - external atmosphere effect", providing a clear theoretical logic for subsequent empirical tests.

3 Data processing

3.1 Model specification

To test the hypotheses, the following two-way fixed effects model (baseline model) is established:

$$SPREAD_{it} = \alpha_0 + \alpha_1 PM25_{it} + \sum_{k=2}^{n} \alpha_k Control_{kit} + \gamma_t + Industry_j + \varepsilon_{it}$$

To test the mediation effects (Hypotheses 2 and 3), the following set of models is constructed:

(1) Mediating variable regression model (third-party certification):

$$THIRD_{it} = \beta_0 + \beta_1 PM25_{it} + \sum_{k=2}^{n} \beta_k Control_{kit} + \gamma_t + Industry_j + \mu_{it}$$

(2) Mediation effect regression model (third-party certification):

$$SPREAD_{it} = \delta_0 + \delta_1 PM25_{it} + \delta_2 THIRD_{it} + \delta_3 \sum_{k=2}^{n} \delta_k Control_{kit} + \gamma_t + Industry_j + \nu_{it}$$

(3) Mediating variable regression model (regional public opinion index):

$$INDEX_{it} = \theta_0 + \theta_1 PM25_{it} + \sum_{k=2}^{n} \theta_k Control_{kit} + \gamma_t + Industry_j + \xi_{it}$$

(4) Mediation effect regression model (regional public opinion index):

$$SPREAD_{it} = \varphi_0 + \varphi_1 PM25_{it} + \varphi_2 INDEX_{it} + \varphi_3 \sum_{k=2}^{n} \varphi_k Control_{kit} + \gamma_t + Industry_j + \omega_{it}$$

3.2 Variable definition

Table 1

Variable Type	Variable Name	Definition and Measurement Method	Data Source
Dependent Variable	Credit Spread(SPREAD)	Issuance spread = Coupon rate - Treasury bond yield of the same maturity in the same period	WIND Database
Independent Variable	PM2.5 Concentration (PM25)	Provincial quarterly average concentration (μg/m^3), calculated as the average of ground monitoring data	China National Environmental Monitoring Centre
Mediating Variables	Third-party Certification (THIRD)	Assigned 1 if third-party certified, otherwise 0	WIND Database
	Environmental Public Opinion Attention (INDEX)	Provincial quarterly average Baidu Index of keywords such as "PM2.5" and "air pollution", standardized by logarithm	Baidu Index Platform
Control Variables - Bond Characteristics	Issuance Scale(SIZE)	Natural logarithm of issuance amount (100 million yuan)	WIND Database
	Bond Rating(CREDIT)	Assigned 5 to 1 in descending order of bond ratings from AAA to A	WIND Database
Control Variables - Macroeconomics	Social Consumption Level(CSMP)	Total social consumption / GDP	National Bureau of Statistics of China
	Industrial Structure(IS)	Tertiary industry output / GDP	National Bureau of Statistics of China
	Financial Development Level(FIN)	Financial institution loans / GDP	National Bureau of Statistics of China
	Human Capital Development Level(HUM)	Natural logarithm of the number of college students per 10,000 people	National Bureau of Statistics of China

4 Empirical analysis

4.1 Data source and descriptive statistics

The sample of this study consists of 2,094 green bonds in China from 2016 to 2022. The data are sourced from the WIND Database, National Bureau of Statistics of China, China National Environmental Monitoring Centre, and Baidu Index Platform. Descriptive statistics (Table 2) show that the dependent variable Credit Spread (SPREAD) has a mean of 4.149 and a standard deviation of 1.302; the independent variable PM2.5 Concentration (PM25) has a mean of 1.378, a standard deviation of 0.512, a minimum value of 0.004, and a maximum value of 3.826. The variable distribution is reasonable, laying a foundation for subsequent analysis.

Table 2 Descriptive statistics

Variable	N	Mean	SD	Min	Max
SPREAD	2094	4.149	1.302	0.730	8.940
PM25	2094	1.378	0.512	0.004	3.826
THIRD	2094	0.401	0.490	0.000	1.000
INDEX	2094	11.530	1.133	5.142	13.780
CREDIT	2094	5.728	0.634	1.000	6.000
SIZE	2094	1.631	1.454	-2.659	5.704
CSMP	2094	0.390	0.055	0.180	0.504
IS	2094	1.737	1.091	0.755	5.244
FIN	2094	3.960	1.394	2.280	7.620
HUM	2094	0.024	0.006	0.010	0.044

4.2 Correlation analysis

Table 2 shows the correlation analysis results. SPREAD is significantly positively correlated with PM25 at the 1% significance level (coefficient = 0.126), which initially supports Hypothesis 1. SPREAD is significantly negatively correlated with CREDIT, SIZE, IS, FIN, and HUM at the 1% significance level, and significantly positively correlated with CSMP at the 1% significance level, which is consistent with theoretical expectations. Additionally, the absolute values of correlation coefficients between variables are mostly less than 0.5, indicating no severe multicollinearity issue.

4.3 Main effect test

The baseline regression results (Table 3) show that after controlling for industry and year fixed effects and other variables, PM2.5 has a significant positive impact on green bond spreads (coefficient = 0.096, $p < 0.05$), verifying Hypothesis 1. A series of robustness tests (coefficient = 0.097, $p < 0.05$ after excluding 2020 epidemic samples; coefficient = 0.079, $p < 0.05$ after replacing the independent variable with PM10) and endogeneity tests using the

Table 3 Correlation analysis

	SPREAD	PM25	THIRD	INDEX	CREDIT	SIZE	CSMP
SPREAD	1						
PM25	0.126***	1					
THIRD	-0.00100	0.058***	1				
INDEX	0.065***	-0.051**	0.0160	1			
CREDIT	-0.341***	-0.0230	-0.145***	0.0310	1		
SIZE	-0.337***	-0.0270	0.086***	0.065***	0.137***	1	
CSMP	0.276***	-0.088***	-0.0180	-0.00700	-0.098***	-0.0270	1
IS	-0.082***	0.107***	0.116***	0.263***	0.095***	0.148***	-0.040*
FIN	-0.216***	0.0240	0.149***	0.260***	0.094***	0.162***	-0.274***
HUM	-0.164***	0.202***	-0.037*	0.076***	0.137***	0.139***	-0.420***

	IS	FIN	HUM
IS	1		
FIN	0.859***	1	
HUM	0.261***	0.268***	1

instrumental variable method (adopting one-period lag of PM2.5 as the instrumental variable, coefficient = 0.116, $p < 0.05$) all confirm the reliability of the conclusion. This indicates that the positive impact of PM2.5 on spreads is not affected by special years, indicator selection, or endogeneity.

Table 4 Baseline regression

	(1)	(2)
	SPREAD	SPREAD
PM25	0.110**	0.096**
	(2.38)	(2.14)
CREDIT		-0.446***
		(-12.54)
SIZE		-0.171***
		(-11.07)
CSMP		1.802***
		(3.59)
IS		0.112**
		(2.48)
FIN		-0.152***
		(-4.25)
HUM		15.220***
		(3.44)
Industry Fixed Effects	controlled	controlled
Year Fixed Effects	controlled	controlled
_cons	3.998***	6.197***
	(59.43)	(17.60)
N	2094	2094
R^2	0.394	0.491

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

4.4 Heterogeneity analysis

The heterogeneity analysis results in Tables 6 and 7 show that the impact of PM2.5 is more significant in eastern regions and non-state-owned enterprises. From the regional perspective, the positive impact coefficient of PM2.5 on spreads in eastern regions is 0.211 ($p < 0.05$), while it is insignificant or negatively correlated in central and western regions. This is because investors in eastern regions have higher risk aversion and are more sensitive to environmental risks. From the perspective of ownership nature, the impact coefficient of PM2.5 on green bonds issued by non-state-owned enterprises is 0.115 ($p < 0.1$), which is higher than that of state-owned enterprises (0.098, $p < 0.1$). The reason is that the credit endorsement of state-owned capital for state-owned enterprises can partially offset the spread pressure caused by pollution risks.

4.5 Mediation effect test

To verify the mediation mechanism of PM2.5 affecting green bond spreads through third-party certification and regional public opinion index, the analysis is conducted with reference to the mediation effect test logic of Jiang (2019), and the results are shown in Table 6.

Table 5 Heterogeneity analysis - bond location

	(1)	(2)	(3)
	东部	中部	西部
PM25	0.211**	-0.146	-0.456***
	(2.51)	(-0.84)	(-3.46)
CREDIT	-0.372***	-0.563***	-0.486***
	(-9.23)	(-5.74)	(-5.40)
SIZE	-0.087***	-0.095**	-0.299***
	(-4.66)	(-2.26)	(-7.04)
CSMP	1.218	-0.968	-2.342
	(1.36)	(-0.56)	(-1.52)
IS	0.054	-1.108**	0.430
	(1.05)	(-2.14)	(0.77)
FIN	-0.084**	-0.070	-0.100
	(-2.03)	(-0.35)	(-0.71)
HUM	8.611	-16.369	43.501**
	(1.27)	(-0.58)	(1.99)
Industry Fixed Effects	controlled	controlled	controlled
Year Fixed Effects	controlled	controlled	controlled
_cons	5.573***	10.423***	8.265***
	(10.73)	(7.13)	(6.76)
N	1342	339	413
R^2	0.498	0.570	0.570

t statistics in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01

Table 6 Heterogeneity analysis - issuer's ownership nature

	(1)	(2)
	State-Owned Enterprises	Non-State-Owned Enterprises
PM25	0.098*	0.115*
	(1.67)	(1.80)
CREDIT	-0.545***	-0.341***
	(-11.44)	(-6.24)
SIZE	-0.240***	-0.038
	(-12.32)	(-1.54)
CSMP	2.574***	-0.049
	(4.29)	(-0.06)
IS	0.064	0.317***
	(1.12)	(3.93)
FIN	-0.103**	-0.133**
	(-2.16)	(-2.51)
HUM	17.591***	4.435
	(3.04)	(0.67)
Industry Fixed Effects	controlled	controlled
Year Fixed Effects	controlled	controlled
_cons	6.547***	5.626***
	(14.96)	(9.48)
N	1357	737
R^2	0.510	0.529

t statistics in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01

As shown in Table 6, PM2.5 significantly reduces the probability of third-party certification for green bonds (β = -0.050, t = -2.03, p < 0.05) and significantly increases the regional public opinion index related to green bonds (β = 0.076, t = 2.26, p < 0.05). This indicates that high PM2.5 concentration affects green bond spreads through two paths: reducing third-party certification and enhancing public opinion attention. The former intensifies information asymmetry due to the lack of certification, while the latter increases investors' concerns about greenwashing risks through public opinion supervision. Both paths ultimately push up spreads, supporting Hypotheses 2 and 3.

5 Conclusion and prospects

5.1 Research conclusion

This study takes 2,094 green bonds in China from 2016 to 2022 as the sample, and comprehensively uses the two-way fixed effects model, mediation effect model, and instrumental variable method to systematically analyze the impact mechanism of PM2.5 concentration on green bond credit spreads. The core conclusions are as follows:

First, PM2.5 concentration has a significant positive impact on green bond credit spreads, verifying Hypothesis 1. The

Table 7 Mediation effect

	(1)	(2)
	THIRD	INDEX
PM25	-0.050**	0.076**
	(-2.03)	(2.26)
CREDIT	-0.023	0.033
	(-1.47)	(1.26)
SIZE	0.042***	0.061***
	(6.20)	(5.32)
CSMP	-0.261	0.886**
	(-1.20)	(2.37)
IS	0.031	0.122***
	(1.59)	(3.62)
FIN	-0.008	0.152***
	(-0.52)	(5.69)
HUM	-6.554***	-3.702
	(-3.25)	(-1.12)
Industry Fixed Effects	controlled	controlled
Year Fixed Effects	controlled	controlled
_cons	0.763***	10.142***
	(5.03)	(38.66)
N	2093	2093
R^2	0.310	0.418

t statistics in parentheses; * p < 0.1, ** p < 0.05, *** p < 0.01

baseline regression results show that after controlling for industry and year fixed effects, bond-specific characteristics (credit rating, issuance scale), and regional macro-characteristics (social consumption level, industrial structure, etc.), each unit increase in PM2.5 concentration significantly increases green bond credit spreads by 0.096-0.110 units (P < 0.05). To ensure the robustness of the conclusion, this study further verifies through three tests: after excluding the 2020 epidemic samples, the PM2.5 coefficient is still 0.097 (P < 0.05); when replacing the independent variable with PM10 concentration, its positive impact on spreads remains significant (coefficient = 0.079, P < 0.05); using the one-period lag of PM2.5 as an instrumental variable to alleviate endogeneity, the results show that each unit increase in PM2.5 significantly increases spreads by 0.116 units (P < 0.05), and the instrumental variable passes the correlation and validity tests. This conclusion indicates that high PM2.5 concentration increases the operational uncertainty of environmental protection projects and reduces investors' trust in environmental performance, ultimately increasing the risk compensation requirement for green bonds.

Second, third-party certification and regional public opinion index play mediating roles in the relationship between PM2.5 and green bond credit spreads, verifying Hypotheses 2 and 3 respectively. The mediation effect test results show that each unit increase in PM2.5 concentration significantly reduces the probability of third-party certification for green bonds by 0.050 units (P < 0.05). As a core mechanism to alleviate information asymmetry, third-party certification can indirectly reduce spreads by improving the quality of environmental information disclosure and reducing liquidity risks. This indicates that issuers in highly polluted areas reduce certification applications due to concerns about project defects being exposed or increased certification costs, ultimately intensifying information asymmetry and pushing up spreads. At the same time, each unit increase in PM2.5 concentration significantly increases the regional public opinion index related to green bonds by 0.076 units (P < 0.05). The increase in public opinion enthusiasm enhances investors' concerns about greenwashing risks, thereby indirectly pushing up spreads, reflecting the external supervision role of public environmental attention on green bond pricing.

Third, the impact of PM2.5 on green bond credit spreads exhibits significant heterogeneity. From the regional perspective, the positive impact of PM2.5 is only significant in eastern regions (coefficient = 0.211, P < 0.05), while the coefficient is insignificant (-0.146, P > 0.1) in central regions and negatively correlated (-0.456, P < 0.01) in western regions. This is closely related to the higher risk aversion and stronger environmental attention of investors in eastern regions. From the perspective of the issuer's ownership nature, green bonds issued by non-state-owned enterprises are more strongly affected by PM2.5 (coefficient = 0.115, P < 0.1) than those issued by state-owned enterprises (coefficient = 0.098, P < 0.1). The reason is that the credit endorsement of state-owned capital for state-owned enterprises can partially offset the spread pressure caused by pollution risks, reflecting the regulatory role of ownership attributes in environmental risk transmission.

5.2 Research prospects

Although this study clarifies the core correlation mechanism between PM2.5 and green bond spreads, there is still room for further expansion. Future research can be deepened from three aspects: the deepening of research perspectives, the optimization of research methods, and the enhancement of practical value.

In terms of research perspectives, we can break through the current limitation of focusing only on regional PM2.5

concentration, introduce micro-characteristic variables of enterprises (such as environmental dimension scores in ESG ratings and the scale of environmental protection investment), explore whether enterprises' active pollution control behaviors can alleviate the impact of PM2.5 on spreads, and enrich the analysis chain of "external environmental pressure-enterprise response behavior-asset pricing". At the same time, the existing study uses Baidu Index to measure public opinion enthusiasm; in the future, text analysis can be used to decompose the sentiment tendency of public opinion content (such as the proportion of positive environmental discussions and negative risk doubts), so as to more accurately capture the impact mechanism of public opinion on spreads. In addition, policy variables such as "dual carbon" policy pilots and local government environmental protection assessment systems can be included to analyze whether policy interventions can adjust the relationship between PM2.5 and spreads, providing more contextualized reference for policy formulation.

In terms of research methods and practical value, the model design can be optimized to solve potential problems. For example, a dynamic panel model (such as system GMM) can be used to capture the long-term lag effect of PM2.5 on spreads, or regression discontinuity design (taking the national standard of PM2.5 concentration as the cutoff point) and difference-in-differences model can be used to more strictly identify the mediation effect, reducing omitted variable bias. The sample can also be expanded to other green financial assets such as green credit and green stocks to compare the transmission differences of environmental risks in different financial markets and reveal the overall impact of environmental factors on the pricing of the green financial system. At the same time, based on the research conclusions, practical applications can be strengthened: assisting financial institutions in developing "PM2.5-credit spread" calculation tools to incorporate environmental risks into the green bond pricing system (for example, setting differentiated environmental risk premium coefficients for green bonds issued by non-state-owned enterprises in eastern regions); providing investors with risk screening indicators including regional PM2.5 average and third-party certification coverage to help them reduce environmental risk exposure; and promoting policy refinement based on heterogeneity conclusions (such as subsidizing the certification costs of green bonds in central and western regions and building an environmental protection information sharing platform to alleviate the financing disadvantage of green bonds in highly polluted areas, while launching special green financing support policies for non-state-owned enterprises to balance the financing cost differences between different ownership entities), so as to contribute to the high-quality development of the green financial market and the realization of the "dual carbon" goals.

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