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Research article

Green finance and firms' pollution emissions: Evidence from Chinese listed firms

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Abstract: Green finance is a key policy tool for sustainable development. The establishment of Green Finance Reform and Innovation Pilot Zones (GFRIPZs) has become an important driver of green growth. In this study, we used data on A-share listed firms from 2012 through 2023 and treated the 2017 launch of the first GFRIPZs as a quasi-natural experiment. We estimated a difference-in-differences (DID) model to measure the effect of green finance on firm-level pollution emissions. The results showed that GFRIPZs significantly reduce pollution emissions among listed firms. These findings hold after several robustness checks. Further analysis showed that the reduction mainly comes from green innovation, especially end-of-pipe treatment technologies. In contrast, source-control technologies show no clear effect. Heterogeneity tests show stronger effects for state-owned firms, large firms, financially constrained firms, firms facing stricter environmental regulation, and firms with greater government attention. Overall, the evidence indicated that green finance reduces pollution and offers policy guidance for China's green transition.

Keywords: green finance; pollution emissions; green innovation; governance path; China

JEL Codes: Q58, Q52, G28, O31

1. Introduction

The global push for sustainable development has led more governments to bring environmental goals into their financial systems. As a key policy tool, green finance directs capital to sustainable industries and projects and helps cut the harms linked to traditional growth models (Hunjra, 2025). This is a new way to connect economic growth with ecological protection, drive green innovation, and support a low-carbon shift in both national and global economies. China has moved quickly in this area. In 2017, the government set up Green Finance Reform and Innovation Pilot Zones (GFRIPZs) in Zhejiang, Jiangxi, Guangdong, Guizhou, and Xinjiang. This step marked a major advance in China's green finance plan, combining central guidance with local trials (Huang et al., 2023). Since then, green finance policies have played an important role in advancing ecological goals and backing China's move toward a green economy. Firms, as main drivers of growth and major sources of pollution, are central to this low-carbon shift, which makes their green transition a policy focus (Fan et al., 2025).

Compared with traditional regulation, green finance offers a modern way to govern the environment and is initiated by the government but runs mainly through market forces. This policy system builds sustainability standards into investment and lending, guiding financial flows toward environmental goals and supporting sustainable growth (Gao et al., 2025; Jiang and Ma, 2025). Yet, micro-level evidence on its environmental effects is scarce. Most researchers have studied its impact on corporate resilience (Yang et al., 2025; Ruan et al., 2025), investment efficiency (Liu and Fang, 2024; Bhatnagar et al., 2025; Kung and Chang, 2025), financing behavior (Zhang, 2023; Li et al., 2025), and innovation (Liu and Wang, 2023; Zhong et al., 2025). Few studies researchers have how green finance reduces firm pollution or test its policy effects. In particular, little is known about its impact on firms' technology choices, such as the tradeoff between source control and end-of-pipe treatment in cutting emissions. Many evaluations of China's green finance pilots use only broad measures, like regional emission totals or macro green indices (He et al., 2023; Li and Xu, 2024; Zhang et al., 2024), which may miss listed firms' responses. Some studies use the China Industrial Enterprise Database or the Annual Tax Survey, but these stop in 2012 and 2016 and cannot capture recent policy effects. Thus, empirical work with up-to-date emission data from listed firms is rare (Fan et al., 2024; Li and Sun, 2025; Hu and Fang, 2025). Most studies of green finance and regulation on emissions rely on panel models or structural methods (Li et al., 2023; Calvia, 2024; Cheng and Jiang, 2024). Some use difference-in-differences to test the 2012 Green Credit Policy (Li et al., 2025; Lu et al., 2025). However, few studies include the 2017 GFRIPZs in one framework to study firm-level emission behavior.

To address this gap, we treat the launch of China's GFRIPZs in 2017 as a quasi-natural experiment. We use panel data from A-share listed firms between 2012 and 2023 and apply a DID approach to test the causal effect of green finance on firm pollution emissions. The results show that GFRIPZs led to a clear drop in firm-level emissions. These results are robust to different model setups and sensitivity tests. The mechanism analysis shows that the decline is mainly driven by more green innovation, especially in end-of-pipe treatment technologies. In contrast, source-control innovation has no significant effect. The heterogeneity analysis shows stronger effects for state-owned enterprises, large firms, firms with tighter financing limits, firms under stricter environmental rules, and firms facing more government oversight.

Compared with the literature, this paper makes the following contributions:

First, we add to the research on green finance policy by moving the focus from the macro level to the firm level. Other researchers have mainly looked at the effects of green finance and regulation on pollution

at a broad scale. Few researchers, however, combine the 2017 GFRIPZs with firm-level emission data in one framework. By treating the GFRIPZ program as a quasi-natural experiment (Zhang et al., 2025), we test the causal effect of green finance on firm pollution and provide new evidence on whether and how financial policy can improve environmental outcomes.

Second, we add to the literature on environmental regulation by building a mechanism in which financial incentives and limits change firms' cost–benefit choices and push them to upgrade green technology (Qi et al., 2023). This adds to the research on command-and-control or tax-based rules and shows that financial policy can act as a market tool for environmental governance.

Third, we add to the research on firm environmental behavior and green innovation by separating source-based from end-of-pipe innovations. The results show that green finance mainly drives end-of-pipe technologies, pointing to a bias in firms' innovation choices that researchers have overlooked. This offers a new view of how financial policy design interacts with firms' environmental strategy.

The remainder of this paper is organized as follows: in Section 2, we provide background on the policy; in Section 3, we present the theoretical framework; in Section 4, we outline the research design; in Section 5, we report the empirical results; and in Section 6, we discuss and conclude the study.

2. Policy background

In recent years, the Chinese government has pushed forward the development of a green financial system to promote ecological goals and support sustainable growth. Green finance refers to financial services and tools that fund environmentally friendly projects. Major products include green credit, green bonds, green equity funds, green insurance, and carbon finance. Its goal is to direct capital toward projects that cut pollution, improve energy use, expand clean energy, protect ecosystems, and build climate resilience. As part of China's carbon peaking and carbon neutrality plans, green finance also works as a system to align financial flows with environmental goals (Huang et al., 2023). Still, the traditional financial system faces challenges. Environmental costs are often ignored, funding for green projects is limited, and environmental risks are not well assessed. These problems show the need for financial tools that can better support a low-carbon transition. To address this, the Guidelines for Establishing the Green Financial System, issued by seven central government bodies in August 2016, proposed the setup of GFRIPZs to test models suited to China's context (Zhong et al., 2025). In June 2017, the State Council approved the first batch of GFRIPZs in eight regions across five provinces: Zhejiang, Jiangxi, Guangdong, Guizhou, and Xinjiang. These zones serve as testing grounds for new institutions and aim at several goals: expanding green products such as credit, bonds, and insurance; improving support systems like environmental disclosure, green certification, and third-party review; and creating market incentives that link finance with environmental goals and guide capital toward energy saving, pollution control, and renewable energy. By adapting policies to local needs, each pilot zone has helped shape a diverse and multi-level green finance system. The GFRIPZs mark a shift from top-down policy to local experiments. This policy setting offers a valuable quasi-natural experiment to study how green finance shapes firm behavior and environmental results. With rising regulation and stronger sustainability demands, a key question for scholars and policymakers is whether green finance can guide listed firms toward green change and emission cuts.

3. Theoretical analysis

The main goal of green finance is to link environmental protection with economic growth by channeling financial resources to sustainable activities (Fan et al., 2025; Zhang et al., 2025). It is expected to help listed firms shift from high-pollution and high-energy production models by reshaping financing structures, tightening market discipline, and improving environmental risk control (Hou et al., 2025). In the GFRIPZs, financial institutions are asked to apply green credit reviews and speed up approval for green projects. They are also encouraged to improve how they identify and assess environmental risks. As a result, high-pollution firms face higher financing bars, stricter compliance rules, and stronger pressure to disclose environmental data. These changes raise outside pressure and push firms to adopt more active pollution control measures. Furthermore, green financial tools such as green credit, bonds, and insurance lower financing costs for green projects and provide risk cover. This expands financial support for environmental management (Zhang, 2023; Li et al., 2025). For high-pollution firms, weak emission control can lead to financial exclusion, reputational loss, and higher compliance risk. Overall, green finance policies mix financial rewards with hidden limits to shape firms' cost–benefit choices, pushing them to cut emissions and follow greener paths.

Green finance shapes corporate environmental behavior directly and indirectly by driving green technological innovation, which helps cut pollution. In theory, green innovation supports environmental protection and economic growth by raising resource efficiency and strengthening pollution control (Zhang et al., 2024). Yet, traditional green innovation often faces long payback periods, high risks, and uncertain returns. These hurdles reduce firms' and banks' willingness to invest in green R&D. As a policy tool, green finance eases these problems by channeling funds and policy support toward green technologies. The GFRIPZs show this role by reducing financing limits and creating a more supportive setting for innovation (Zhang, 2023; Li et al., 2025). They also push for stronger environmental disclosure, which guides firms to set innovation priorities more clearly. Under regulatory and market pressure, firms are driven to adopt technologies that meet rules and improve their public image. Green financial tools cut the costs of developing such technologies. More importantly, green innovation builds core competitiveness through technology growth and green brand value, giving firms long-term strategic benefits. In short, by removing barriers, lowering costs, and backing green R&D, green finance plays a lasting role in reducing corporate emissions (Zhang and Guo, 2025).

Although green finance can cut pollution by encouraging green innovation, its effects may vary depending on firms' technology choices (Zhu et al., 2025). In practice, under policy pressure and limited resources, firms often favor end-of-pipe technologies, such as flue gas desulfurization or wastewater treatment, because they cost less, are quicker to apply, and carry lower risk. These technologies let firms respond rapidly to the credit and regulatory incentives of green finance. While they work well for short-term emission cuts, they have limited ability to reform production processes or reduce pollution at the source (Qi et al., 2023). In contrast, source-level innovations, such as process redesign, raw material substitution, and energy structure changes, need bigger investments, longer development periods, and more technical skills. Current green finance policies struggle to identify, evaluate, and support these upstream technologies. Ambiguous definitions of "green projects" and information gaps let some firms gain low-cost funding through greenwashing without real environmental gains, reducing financial efficiency (Hu et al., 2025). Differences in local government priorities and discretionary implementation also weaken policy consistency and long-term results (Qi

et al., 2023). Therefore, while green finance has made early progress in promoting corporate green transformation, policies need to refine technology pathways, incentive designs, and regulatory frameworks. Future policies should give stronger guidance and financial support for upstream green technologies, set up dynamic performance evaluation systems, and ensure that environmental governance delivers meaningful and lasting outcomes.

Beyond the average effect, the impact of green finance reforms differs across firms and regions. This variation can be explained by several factors. First, ownership matters: State-owned enterprises (SOEs) usually align more closely with government goals and face stronger political and social accountability. Because green finance mixes financial incentives with implicit regulatory pressure, SOEs are more likely to respond and pursue stronger green innovation, especially end-of-pipe technologies that deliver quick and visible results (Wang, 2025). Second, firm size shapes policy effects: Larger firms generally have better access to finance, stronger technology capabilities, and more advanced environmental management systems (Gao et al., 2025). These advantages support costly green R&D and expose firms to higher public and regulatory scrutiny, making finance-driven green innovation more evident. Third, financial constraints affect resource allocation: Since the GFRIPZs lower financing costs for green projects, firms with tighter credit limits are more likely to direct marginal capital toward pollution control and green patents. This shows how easing financial bottlenecks encourages green innovation. Finally, institutional and regulatory environments are key: In regions with stricter environmental rules or stronger government oversight, green finance works together with command-and-control measures, increasing firms' incentives to adopt green technologies and reduce emissions. In contrast, where enforcement is weak, green finance alone may have limited impact. Overall, differences in ownership, firm size, financial capacity, and regulatory context reflect core ways that green finance shapes corporate environmental behavior. Figure 1 illustrates the logical framework for how GFRIPZs reduce pollution among listed firms.

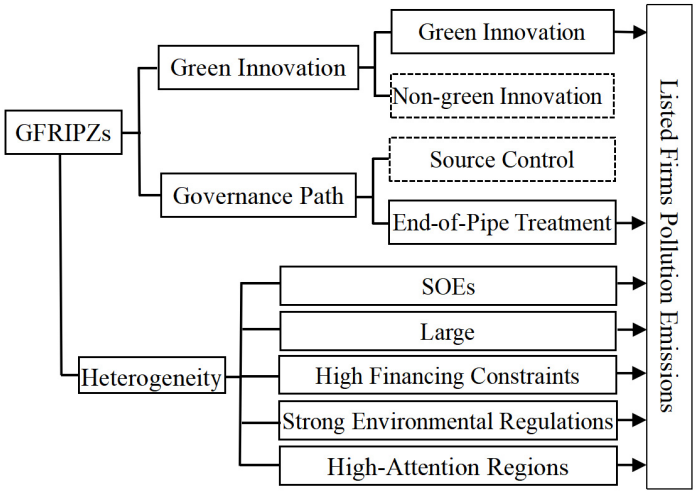

Figure 1. Logical framework diagram.

4. Research design

4.1. Data sources

We use panel data from A-share listed companies from 2012 to 2023 to examine how GFRIPZs affect corporate pollution emissions. Financial data are sourced from the China Stock Market & Accounting Research (CSMAR) database. To ensure robust results, the following data processing steps are applied: (1) Firms labeled as ST or *ST, and those delisted during the sample period, are excluded; (2) financial sector firms are removed; (3) continuous variables are winsorized at the 1st and 99th percentiles to reduce outlier effects; and (4) absolute-value variables are log-transformed to address heteroskedasticity caused by large fluctuations. After these steps, the final sample includes 15,595 firm-year observations. All analyses are performed using STATA 15.0.

4.2. Variable selection

4.2.1. Explained variable

The dependent variable in this study is firm-level pollution emission intensity (PE). Following China's Administrative Measures for the Collection of Pollution Discharge Fees, emissions of several pollutants are converted into a single pollution-equivalent index. The pollutants include chemical oxygen demand (COD) and ammonia nitrogen in industrial wastewater, as well as sulfur dioxide (SO_2) and nitrogen oxides (NOx) in industrial waste gas. Each pollutant is first standardized, and the standardized values are summed to create an overall measure. To avoid taking the logarithm of zero, one is added to the total before applying the natural log transformation. This gives the final measure of a firm's overall pollution emission intensity.

4.2.2. Explanatory variables

The main explanatory variable in this study is the establishment of the GFRIPZs. A policy dummy, Treat, equals 1 for firms located in any of the eight pilot zones across five provinces and autonomous regions, Zhejiang, Jiangxi, Guangdong, Guizhou, and Xinjiang, and 0 otherwise. A time dummy, Post, equals 1 for 2017 and later years, and 0 for the pre-policy period. The interaction between Treat and Post captures the effect of the green finance reform in a DID framework. A significantly negative coefficient on this DID term indicates that the green finance policy successfully reduced firm-level pollution emissions (Fan et al., 2025; Han and Li, 2025; Xu et al., 2025).

4.2.3. Control variables

To rigorously examine the impact of the GFRIPZs on firm pollution reduction, we include control variables that capture firm characteristics, financial conditions, and governance features. These factors may independently influence firms' emission behavior. Firm size (Size) is measured as the natural log of total assets at year-end. Larger firms usually have more financial and technological capacity to meet environmental standards and face stricter regulatory oversight. Firm age (Age), calculated as the observation year minus founding year plus one, reflects a firm's life cycle stage. Older firms often have

more mature management practices and experience in environmental governance. The debt ratio (Debt), defined as total liabilities divided by total assets, captures financial constraints that may limit investment in pollution control. Ownership concentration (Top1) measures the share of the largest shareholder. While higher concentration can improve decision-making efficiency and accountability, it may discourage long-term green investments if controlling shareholders focus on short-term gains. Profitability, measured by return on assets (Roa), is included because more profitable firms can better fund green innovation and emission reduction. Capital intensity (Capital), calculated as net fixed assets divided by total assets, proxies for production structure and is often linked to higher emissions in capital-intensive industries. Return on capital (Roc), defined as earnings before interest and taxes divided by total assets, reflects capital use efficiency, which may affect technological upgrading and pollution outcomes. Controlling for these variables enables us to account for firm-level heterogeneity and more accurately identify the causal effect of green finance policies on pollution reduction. Detailed variable definitions are shown in Table 1.

Table 1. Variable design.

Variable	Obs	Processing method
Pollution emissions	PE	For specific Settings, please refer to 4.2.1
Green finance	Treat*Post	Firms in regions that have implemented GFRIPZs as to 1, otherwise, as to 0
Enterprise scale	Lnsize	Total assets are logarithmic
Age of establishment	Lnage	Logarithmic (the age of establishment of the firm +1)
Firm liabilities	Debt	Total liabilities/total assets
Equity concentration	Top1	The shareholding ratio of the largest shareholder
Return on assets	Roa	Net profit/total assets
Capital intensity	Capital	Net fixed assets/Total assets
Return on capital	Roc	Ebit/Total assets

Table 2 presents the descriptive statistics for all variables. The mean pollution emission level of listed firms is 9.9745, ranging from 0.0000 to 16.5433. The standard deviation is 1.1212.

Table 2. Statistics.

Variable	Obs	Mean	Standard deviation.	Minimum	Maximum
PE	15595	4.9745	1.1212	0.0000	16.5433
Treat*Post	15595	0.1833	0.5567	0.0000	1.0000
Lnsize	15595	23.1124	1.3331	18.8966	26.9644
Lnage	15595	2.8988	0.3533	1.0986	3.78545
Debt	15595	0.4988	0.2333	0.0343	0.9123
Top1	15595	33.5442	14.3514	0.0028	0.8455
Roa	15595	0.0322	0.0654	−0.2655	0.7744
Capital	15595	0.2422	0.1653	0.0033	0.8123
Roc	15595	0.0544	0.0844	−0.3855	0.8711

4.3. Model setting

To assess the impact of GFRIPZ on firm pollution reduction, we employ a DID model, as specified in Equation (1). To address potential confounding factors, the baseline DID is complemented with several robustness checks, including an event-study design to capture dynamic effects, controls for concurrent green policies, and a propensity score matching difference in differences (PSM-DID) approach to reduce sample selection bias.

$$PE_{it} = \alpha_0 + \beta_1 \mathrm{Treat}_i \times \mathrm{Post}_t + \gamma Control_{it} + year_t + firm_i + \varepsilon_{it}. \quad (1)$$

Among them, $i\ and\ t$ represent the listed firm and the year, respectively. PE_{it} represents the pollution emission level of listed firms as a dummy variable, $\mathrm{Treat}_i \times \mathrm{Post}_t$ represents the green finance, $Control_{it}$ as a series of added control variables, $year_t$ represents the time fixed effect, $firm_i$ represents the enterprise fixed effect, and ε_{it} represents the error.

5. Empirical results

5.1. Benchmark regression

Table 3. Benchmark regression.

PE	(1)	(2)
Treat*Post	−0.0422***	−0.0352***
	(0.0135)	(0.0105)
Lnsize		−0.3112***
		(0.1081)
Lnage		0.2177
		(0.2473)
Debt		0.1335**
		(0.0601)
Top1		−0.1375
		(0.2455)
Roa		−0.2119***
		(0.0759)
Capital		−0.0188
		(0.0284)
Roc		0.0387
		(0.0444)
Constant	0.9766***	1.3422***
	(0.3045)	(0.4031)
Fixed year	Control	Control
Fixed firm	Control	Control
R-squared	0.7789	0.7641
Observations	15595	15595

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation.

Columns (1) and (2) of Table 3 show the estimated effects of the GFRIPZs on firm-level pollution emissions, without and with control variables, respectively. The results indicate that the GFRIPZs significantly reduce listed firm pollution, with coefficients significant at the 1% level in both models. In column (2), which includes firm-level controls, the green finance reform is associated with an average reduction of 3.52% in firm emissions. These findings suggest that green finance policies are an effective tool for promoting micro-level environmental governance and substantially strengthening firms' efforts to cut pollution.

5.2. Robustness test

5.2.1. Parallel trend test

The validity of the DID approach relies on the assumption that the treatment and control groups would have followed parallel trends without the policy. To test this, an event-study design is employed, using dummy variables for each year before and after the GFRIPZs to capture their dynamic effects on firm-level pollution emissions. The year 2016, immediately before the policy, is used as the reference period. As shown in Figure 2, no significant differences in emissions exist between the treatment and control groups during the pre-policy period. Beginning in 2017, emissions in the treatment group drop sharply, and the downward trend strengthens in the following years. The estimated coefficients are statistically significant. These results support the parallel trends assumption, confirm the dynamic emission-reducing effects of the GFRIPZs, and reinforce the credibility of the major findings.

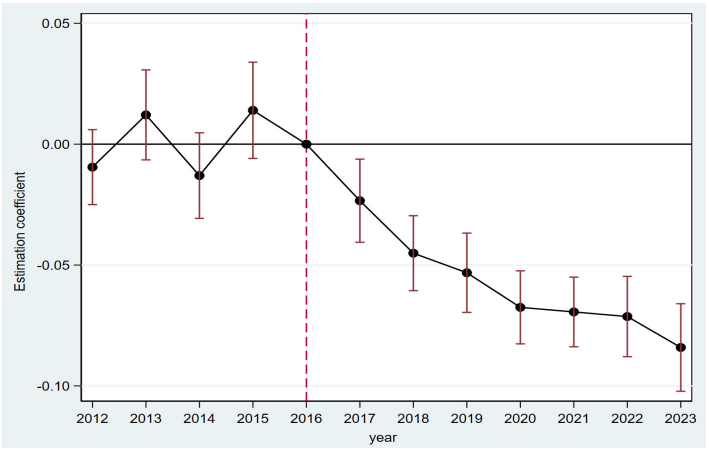

Figure 2. Parallel trend test.

5.2.2. IV Estimation

To address potential endogeneity in the policy assignment of the GFRIPZs, we employ an instrumental variable (IV) approach based on geographic proximity. The instrument is a binary variable indicating whether a firm's registered location is within 150 kilometers of the nearest GFRIPZ pilot city. This distance threshold is chosen based on economic geographic reasoning: It captures a meaningful spatial boundary where policy spillover effects, such as knowledge diffusion, credit

allocation, and regulatory cooperation, are most likely, while remaining exogenous to firm-level pollution emissions. The instrument is constructed using geographic information system (GIS) coordinates: We first compute the spherical distance between each firm's registered address and each pilot city, then assign 1 if the minimum distance is within 150 km, and 0 otherwise. We argue that this instrument satisfies the relevance condition because firms near pilot zones are more directly affected by green finance policies and institutional innovations. It also likely meets the exclusion restriction since geographic distance, after controlling for regional economic factors and firm characteristics, affects pollution emissions mainly through policy exposure rather than other direct channels. Columns (1) and (2) of Table 4 show that the first-stage regression results confirm a strong positive correlation between the instrument and the treatment variable. Weak-instrument tests, including a Cragg-Donald F-statistic well above conventional thresholds, support the strength of the instrument, and endogeneity tests justify the IV approach. Importantly, the IV estimates are consistent with the baseline difference-in-differences results, reconfirming that green finance significantly reduces firm-level pollution emissions. These findings address endogeneity concerns, such as non-random policy placement, and reinforce the causal interpretation of the policy effect.

Table 4. Estimation of instrumental variables.

Variable	(1)	(2)
IV Estimation	The first stage	The second stage
	GFRIPZs	PE
IV	0.0544**	
	(0.0249)	
Treat*Post		−0.0323**
		(0.0101)
Kleibergen-Paap Wald rk F statistic	1221.2354	
Kleibergen-Paap rk LM statistic		433.7866
Control variable	Control	Control
Fixed year	Control	Control
Fixed firm	Control	Control
R-squared	−	0.5557
Observations	15595	15595

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

5.2.3. Addition of city control variables

To account for potential confounding effects of regional macroeconomic factors on firm-level pollution emissions, city-level control variables are added to the baseline regression to improve identification accuracy and robustness. The regional characteristics include industrial structure upgrading, measured by the ratio of tertiary to secondary industry output; regional economic development, proxied by per capita GDP; financial development, defined as the ratio of total loans by financial institutions to regional GDP; and government intervention, captured by the share of local fiscal expenditure in regional GDP. As shown in column (1) in Table 5, the effect of the GFRIPZs on

firm pollution emissions remains negative and statistically significant after including these city-level controls. This result further confirms the robustness of the major findings.

Table 5. Robustness test.

Robustness Test	(1)	(2)	(3)	(4)	(5)
	Add cities control variables	PSM-DID	Exclude other concurrent policies		
Treat*Post	−0.0311*** （0.0114）	−0.0288*** （0.0101）	−0.0344*** （0.0119）	−0.0325*** （0.0118）	−0.0301*** (0.0096)
Control variable	Control	Control	Control	Control	Control
Fixed year	Control	Control	Control	Control	Control
Fixed firm	Control	Control	Control	Control	Control
R-squared	0.7896	0.7896	0.8876	0.7896	0.7966
Observations	15595	6240	15595	15595	15595

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

5.2.4. PSM-DID

To address potential endogeneity from sample selection bias, we combine propensity score matching (PSM) with the DID approach. A matched sample is created using the one-to-one nearest-neighbor matching based on observable firm characteristics. Firms that cannot be matched are excluded. The DID estimation is then applied to the matched sample. As shown in column (2) in Table 5, the GFRIPZs have a statistically significant negative effect on firm-level pollution emissions. The direction and size of the coefficient are consistent with the baseline results, indicating that green finance policies reduce emissions even after accounting for observable differences between firms. These findings further confirm the robustness and reliability of the main results.

5.2.5. Exclusion of other concurrent policies

To ensure the accuracy of the estimated policy effects, we also control for the potential influence of other major environmental regulations during the sample period. The Environmental Protection Tax Law of the People's Republic of China, enacted in 2018, represents the most stringent environmental tax policy in China to date. By substantially raising pollution costs, it increases firms' incentives to improve environmental governance and may directly affect emission levels. In this study, a dummy variable for the environmental protection tax is included, coded as 1 for firms in cities that raised the environmental tax rate since 2018, and 0 otherwise. Similarly, the Air Pollution Prevention and Control Action Plan (the "Air Ten Measures"), introduced by the State Council in 2013, establishes a strict national framework to reduce emissions through stronger enforcement. A corresponding dummy variable is assigned 1 for firms in cities where the plan is implemented, and 0 otherwise. Furthermore, to encourage banks to develop green credit services, the former China Banking Regulatory

Commission issued the Guidelines for Establishing the Green Financial System (the "Guidelines") in 2012. This policy helps mitigate environmental and social risks and supports the transition to a green economy. Based on industry classifications in the Guidelines and following existing literature, a green credit dummy variable is constructed, equal to 1 for firms in sectors targeted by the green credit policy, and 0 otherwise. This variable is also included in the model as a control. As shown in columns (3) and (5) in Table 5, even after controlling for these concurrent regulations, the GFRIPZs continue to have a statistically significant negative effect on firm-level pollution emissions. This further confirms the robustness of the major findings.

5.2.6. Placebo test

To further test the robustness of the regression results and reduce potential biases, we conduct a placebo test along two dimensions: Random assignment of pilot regions and random assignment of policy timing. In the random assignment of pilot regions, a number of cities equal to the actual number of pilot zones are randomly selected to form a pseudo-treatment group, while the remaining cities serve as the control group. A simulated policy dummy is created, and the DID model is estimated. This procedure is repeated 500 times. In the random assignment of policy timing, the actual pilot regions are retained, but the policy implementation year is randomly reassigned. The DID estimation is repeated for 500 iterations using this falsified timing. As shown in Figures 3 of A and B, the density curves of the estimated coefficients from both placebo tests approximate a normal distribution centered around zero. In both cases, the actual estimated coefficient lies far outside the placebo-generated distribution. Additionally, the distributions of p-values show that most simulated estimates are statistically insignificant at conventional levels. These results suggest that the observed emission reduction effect of the GFRIPZs is unlikely to be driven by random chance or unobserved confounding factors, reinforcing the credibility and robustness of the causal findings.

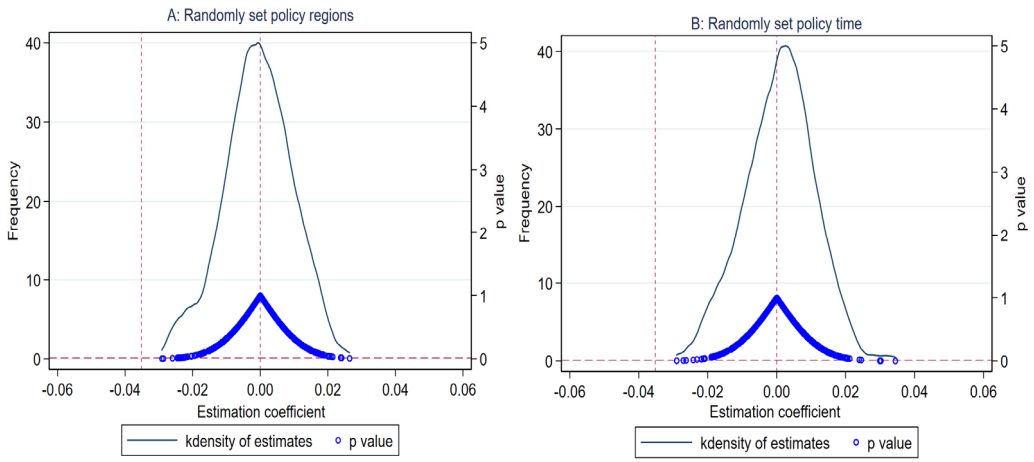

Figure 3. Placebo test.

5.3. Heterogeneity test

5.3.1. Heterogeneity of ownership

To examine the heterogeneous effects of green finance policies across ownership types, we compare the impact of the GFRIPZs on pollution emissions between state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs). As shown in Table 6, the GFRIPZs significantly reduce emissions among SOEs at the 1% level. In contrast, the effect is statistically insignificant for non-SOEs, indicating a weaker response in this group. This divergence can be attributed to fundamental differences in institutional embeddedness and resource dependence. SOEs, as integral components of China's administrative system, are subject to strong "institutional isomorphism," which compels them to pursue policy goals alongside profitability. Their entrenched political affiliations ensure preferential access to policy-directed financial resources, thereby enhancing their capacity to undertake green initiatives. In contrast, non-SOEs operate under tighter financing constraints and remain on the periphery of the administrative resource allocation network. Consequently, non-SOEs not only lack the financial capacity for substantial environmental investment but also face weaker coercive pressure to align with national sustainability agendas, significantly limiting the effectiveness of green finance policies for this group.

Table 6. Heterogeneity of ownership.

Heterogeneity of ownership	(1)	(2)
	SOEs	Non-SOEs
Treat*Post	−0.0544*** （0.0148）	−0.0212 （0.0307）
Control variable	Control	Control
Fixed year	Control	Control
Fixed firm	Control	Control
R-squared	0.8798	0.7798
Observations	4990	10605

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

5.3.2. Heterogeneity in enterprise scale

To assess the heterogeneous effect of firm size on the effectiveness of green finance, firms are classified as large or small based on whether their total assets in 2016 exceed the sample median. As shown in Table 7, the GFRIPZs significantly reduce pollution emissions among large firms, with the effect significant at the 1% level. In contrast, the impact on small firms is statistically insignificant. This disparity highlights the resource-allocation role of green finance, which tends to favor firms with greater financial and organizational capacity. Large firms can better leverage green credit incentives and green bond financing due to their higher creditworthiness and more developed environmental,

social, and governance (ESG) systems. Their superior access to policy information and specialized financial instruments, such as sustainability-linked loans, facilitates the adoption of emission-reducing technologies. Small firms, however, often lack sufficient collateral, established credit histories, or internal expertise to fully use green financing. Structural barriers, including high transaction costs, information asymmetry, and limited bargaining power, further limit their responsiveness to green finance policies. These results emphasize the need to design inclusive financial instruments, such as targeted credit guarantees, low-interest loans, and technical support programs, to enable small and medium-sized enterprises (SMEs) to participate effectively in the transition toward green development.

Table 7. Heterogeneity of the enterprise scale.

Heterogeneity of firm scale	(1)	(2)
	Large	Small
Treat*Post	−0.0378***	−0.0201
	(0.0116)	(0.0209)
Control variable	Control	Control
Fixed year	Control	Control
Fixed firm	Control	Control
R-squared	0.8796	0.7898
Observations	7173	8422

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

5.3.3. Heterogeneity of financing constraints

To evaluate the heterogeneous effect of financial constraints on the effectiveness of green finance, firms are divided into high- and low-financing constraint groups based on whether their SA index in 2016 is above the sample median (Hadlock and Pierce, 2010). Regression results in columns (1) and (2) in Table 8 show that the GFRIPZs significantly reduce pollution emissions in both groups, with coefficients significant at the 1% level. This indicates that the policy promotes emission reduction regardless of firms' financing constraints. To further investigate this mechanism, an interaction term between the policy dummy and the high-constraint group is included. As shown in column (3) in Table 8, the negative and significant coefficient on this term indicates that the emission reduction effect is stronger for financially constrained firms. This suggests that green finance helps ease credit barriers by improving access to green credit, lowering financing costs for environmental projects, and reducing credit rationing, thereby enabling constrained firms to invest more in pollution control technologies. Overall, these results highlight the credit-easing role of green finance, which is particularly effective for firms facing financial limitations, and underscore its potential to correct market failures in environmental investment (Zhang, 2023; Li et al., 2025).

Table 8. Heterogeneity of financing constraints.

Heterogeneity of financing constraints	(1)	(2)	(3)
	High financing constraints	Low financing constraints	
Treat*Post	−0.0578***	−0.0433**	−0.0122
	(0.0157)	(0.0195)	(0.0137)
Treat*Post*SA			−0.0213**
			(0.0095)
SA			0.0098
			(0.0114)
Control variable	Control	Control	Control
Fixed year	Control	Control	Control
Fixed firm	Control	Control	Control
R-squared	0.7789	0.7876	0.8733
Observations	6705	8890	15595

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

5.3.4. Heterogeneity of environmental regulations

To assess the heterogeneous effect of regional environmental regulation intensity, cities are classified as high- or low-intensity based on whether their per capita environmental protection expenditure in 2016 exceeds the sample median. As shown in Table 9, the GFRIPZs significantly reduce firm-level pollution emissions in regions with strict environmental regulation, with the coefficient significant at the 1% level. In contrast, the effect is insignificant in regions with weaker regulation. This pattern highlights the complementary relationship between green finance and environmental regulation. In high-intensity regions, strong regulatory pressure encourages firms to adopt cleaner technologies and practices, while green finance eases financial constraints by providing targeted credit, lowering financing costs for environmental projects, and improving access to green investments. In contrast, in regions with weak enforcement, firms face lower costs for non-compliance, reducing their motivation to invest in emission reduction. These results indicate that green finance is most effective when embedded in a supportive regulatory environment, where financial incentives and environmental oversight jointly promote corporate green transformation.

Table 9. Heterogeneity of environmental regulations.

Heterogeneity of environmental regulations	(1)	(2)
	Strong environmental regulations	Weak environmental regulations
Treat*Post	−0.0554***	−0.0942
	(0.0177)	(0.1682)
Control variable	Control	Control
Fixed year	Control	Control
Fixed firm	Control	Control
R-squared	0.7786	0.8743
Observations	6861	8734

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

5.3.5. Heterogeneity of government attention

To evaluate the role of local governments in implementing green finance policies, we conduct a heterogeneity analysis based on the level of governmental attention to environmental issues. Local government work reports, which reflect municipal policy priorities, are used to measure environmental regulatory intensity (Jiang and Zhang, 2020). Following Yu et al. (2021), we count the frequency of 15 environment-related keywords in each report. The ratio of these keywords to the total word count serves as a proxy for governmental environmental attention. The sample median value for 2016 is used as the classification benchmark. Cities with ratios above this benchmark are classified as high-attention regions, and those below as low-attention regions. As shown in Table 10, the GFRIPZs significantly reduce firm-level pollution emissions in high-attention regions, with the effect significant at the 1% level. These findings suggest that green finance policies are more effective when local governments prioritize environmental governance. This stronger effect likely results from governments' active roles in policy promotion, resource allocation, and enforcement. In high-attention regions, greater administrative and political resources support green development, increasing supervisory pressure and firms' responsiveness to financial incentives. Conversely, regions with lower governmental attention face weaker regulatory coordination and fewer compliance incentives, which limits the impact of green finance policies.

Table 10. Heterogeneity of government attention.

Heterogeneity of government attention	(1)	(2)
	High-attention regions	Low-attention regions
Treat*Post	−0.0419***	−0.0124
	(0.0131)	(0.0129)
Control variable	Control	Control
Fixed year	Control	Control
Fixed firm	Control	Control
R-squared	0.7896	0.7854
Observations	7329	8266

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

5.4. Mechanism analysis

5.4.1. Green innovation

To understand how the GFRIPZs contribute to listed firm pollution reduction, we examine whether the policy promotes emission mitigation through green innovation. Green and non-green innovation are measured using the number of corresponding patent applications. As shown in Table 11, the GFRIPZs significantly increase listed firms' green innovation, with coefficients statistically significant at the 1% level. In contrast, the policy does not significantly affect non-green patents, indicating that non-green innovation is not a primary channel through which green finance influences corporate environmental behavior. These results highlight the role of green finance in directing firm-level resources toward environmentally sustainable technological development. Beyond easing financing constraints, GFRIPZs effectively encourage research and development in green technologies, generating substantial environmental benefits and supporting long-term pollution control and sustainable growth. In summary, green finance fosters a positive cycle linking environmental and economic transformation through capital guidance, green innovation, and emission reduction (Zhang et al., 2024).

Table 11. Mechanism analysis: Green innovation.

Mechanism analysis	(1)	(2)
	Green innovation	Non-green innovation
Treat*Post	0.0655***	0.0341
	(0.0194)	(0.0516)
Control variable	Control	Control
Fixed year	Control	Control
Fixed firm	Control	Control
R-squared	0.7786	0.7934
Observations	15595	15595

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

5.4.2. Governance path

When analyzing how green finance reform reduces pollution, it is important to consider not only the overall level of green innovation but also its technological focus; specifically, whether it emphasizes source control or end-of-pipe treatment (Zhu et al., 2025). We examine firm-level green technological innovation by identifying green patents according to the World Intellectual Property Organization (WIPO) environmental technology classification system, established in 2010. Consistent with the UNFCCC, WIPO categorizes green technologies into seven domains, including alternative energy, transportation, waste management, and energy efficiency, covering around 200 environment-related technical fields. Using this framework, we construct a firm-level green innovation dataset for Chinese A-share listed companies and classify patents into two types: Source control and end-of-pipe treatment. Source control innovations aim to prevent pollution at its origin, for example by improving fossil fuel efficiency or developing renewable energy technologies such as solar, wind, biomass, and hydrogen. End-of-pipe technologies mitigate emissions at the final stage of production, including gas and dust removal in steelmaking, wastewater treatment, sanitation infrastructure, and flue gas desulfurization. The share of source control and end-of-pipe patents in a firm's green portfolio serves as a proxy for its innovation orientation. As shown in Table 12, the GFRIPZs significantly promote end-of-pipe green innovation, which is linked to substantial reductions in corporate pollution emissions. While the coefficient for source control innovation is negative, it is not statistically significant, indicating a weaker policy effect in this area.

This difference in policy effectiveness reflects fundamental distinctions between the two types of innovation and the current design of green finance mechanisms. Source control technologies usually require major changes to production processes, higher upfront costs, longer payback periods, and greater technological uncertainty compared with end-of-pipe solutions. Green finance evaluation frameworks often prioritize short-term environmental performance and easily measurable emission reductions, which naturally favor end-of-pipe technologies that deliver immediate results. Financial institutions also face difficulties in accurately assessing the feasibility and environmental benefits of process innovations, creating information asymmetries that disadvantage source control projects in credit allocation. Consequently, firms, particularly those under profitability pressure, tend to choose end-of-pipe solutions that meet regulatory requirements with lower investment and faster

implementation, rather than pursuing riskier but potentially transformative source innovations (Qi et al., 2023; Zhu et al., 2025).

Table 12. Mechanism analysis: governance path.

Mechanism analysis	(1)	(2)
	Source control	End-of-pipe treatment
Treat*Post	0.0187	0.2355***
	(0.0339)	(0.0754)
Control variable	Control	Control
Fixed year	Control	Control
Fixed firm	Control	Control
R-squared	0.8768	0.7875
Observations	15595	15595

Note: *, **, and *** represent significance levels of 10%, 5%, and 1%, respectively. The parentheses are standard errors. The model uses the enterprise level for robust clustering standard estimation. For the sake of simplicity, the reporting results of control variables are omitted.

6. Discussions and conclusions

6.1. Discussions

6.1.1. Policy implications

Our empirical results provide clear, actionable guidance for refining China's green finance policy framework. The finding that pollution reduction is primarily driven by end-of-pipe technologies, while source-control innovation shows no significant effect, suggests a critical misalignment in current financial support. Therefore, policymakers should rebalance incentives to favor source-prevention technologies. This can be achieved by optimizing targeted relending facilities for R&D in areas such as green hydrogen and carbon capture, establishing dynamic green portfolio evaluations that prioritize carbon performance, and introducing green bond discounts specifically for long-term, preventive green projects. Such reorientation would help shift capital from downstream treatment to upstream avoidance, directly supporting carbon neutrality goals.

Furthermore, the observed heterogeneity in treatment effects calls for a more equitable and well-targeted policy design. Given that state-owned enterprises, large firms, and those facing stricter regulation exhibit stronger responses, there is a risk that green finance benefits may become concentrated among incumbents. To improve inclusiveness, a defined portion of green credit and bond quotas should be reserved for SMEs. Governments can further lower barriers by establishing certification and disclosure platforms that reduce compliance costs. Furthermore, the stronger effects seen under stricter regulation and greater government attention highlight the importance of policy synergy. We recommend enhancing coordination between green finance, environmental regulation, and carbon markets, for instance by linking green credit conditions to firms' carbon market performance or embedding financial instruments within regional carbon peaking plans.

Finally, a robust disclosure and rating system is essential to ensure integrity and effectiveness. To prevent greenwashing and ensure resources flow to truly green projects, mandatory disclosure of key pollutants and carbon emissions should be implemented, alongside unified green certification standards. Introducing third-party assessments of policy performance and making results public will strengthen accountability. A transparent information infrastructure will help green finance function as an efficient market mechanism, ensuring it effectively supports the real economy's green transition.

6.1.2. Limitations and future studies

While this study provides robust micro-level evidence on the effects of green finance on listed firms' pollution emissions, several limitations should be noted, offering opportunities for future research. First, the findings and policy implications are mainly based on China's GFRIPZs. China's unique institutional setting, policy framework, and stage of economic development may limit the applicability of these results to other countries or regions. In future research, researchers could extend this work through cross-country comparisons, especially between emerging and developed economies, to explore how green finance mechanisms operate in different contexts. Second, although we propose policy recommendations to enhance the effectiveness of green finance, some suggestions, such as developing advanced financial instruments or coordinating policies across regions, may require further refinement before practical implementation. In future studies, researchers could design operational frameworks that clarify stakeholder responsibilities and assess the feasibility of policies under different fiscal and regulatory conditions. Additional work should also entail establishing precise green identification standards, dynamic evaluation systems, and stronger coordination between green finance and other environmental policies. Research on improving green finance access for small and medium-sized enterprises (SMEs) would further support theoretical and practical progress in this field.

6.2. Conclusions

In this paper, we use a quasi-natural experiment based on the GFRIPZs to evaluate the impact of green finance on listed firm pollution reduction and its underlying mechanisms. The results show that green finance significantly lowers firms' pollution emissions and improves environmental performance. This effect is mainly driven by green innovation, especially end-of-pipe treatment technologies. The findings contribute to the theory of green finance and demonstrate how financial instruments can support the transition toward sustainable development. The policy effects are stronger for state-owned enterprises, large firms, financially constrained firms, and firms in regions with stricter environmental regulations or higher government attention to environmental issues. This heterogeneity highlights the importance of considering firm characteristics and regional institutional contexts when designing effective policies. The significant role of local government focus and regulatory strictness emphasizes the critical influence of the institutional environment in ensuring successful implementation of green finance. Overall, this study provides robust empirical evidence for expanding and refining China's green finance reforms. It also offers practical insights for developing green financial systems and strategies for sustainable growth worldwide. In future policies, leaders should prioritize support for source-oriented green innovation, strengthen coordination between green finance and environmental regulation, and promote technological upgrading alongside pollution reduction.

Author contributions

Bin Pan: Conceptualization, investigation, supervision, review writing, and funding acquisition. Jiqiang Huang: Investigation, data collection, original draft writing, review writing and editing. Supu Xie: Methodology, data analysis, result interpretation, and validation.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

All authors declare no conflicts of interest in this paper.

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