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The Impact and Mechanism of Green Bonds on Corporate Carbon Emissions—An Empirical Study of Multi-Period DID under the TOE Framework and Taking into Account TWFE Weighted Decomposition

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Abstract. Green finance is widely regarded as an important policy tool for promoting the low-carbon transformation of enterprises, but its micro-governance effects and intrinsic mechanisms still need systematic testing. Based on data from A-share listed companies in Shanghai and Shenzhen from 2010 to 2023, this paper uses green bond policy as a quasi-natural experiment and employs a difference-in-differences model to identify the impact of green bonds on corporate carbon emissions. The study finds that green bond issuance significantly reduces corporate carbon emissions, a conclusion that holds true after multiple robustness tests. Mechanism testing shows that green bonds reduce corporate carbon emissions by alleviating corporate financing constraints, strengthening green investment incentives, promoting the simultaneous improvement of the quantity and quality of green innovation, and enhancing executives' green awareness. Further heterogeneity analysis based on the TOE framework reveals that the above-mentioned emission reduction effects are more significant in enterprises with higher levels of digital transformation, sufficient reserves of high-tech talent, strong risk-bearing capacity, and better ESG performance, as well as in regions with higher industry competition intensity and higher levels of environmental regulation. This paper reveals the path of green bonds in reducing corporate carbon emissions from a comprehensive perspective of the linkage between financing structure optimization, corporate governance improvement, and green technology innovation, providing new empirical evidence for improving the green finance system and promoting corporate green development.

Keywords: green bonds; corporate carbon emissions; TOE framework; difference-in-differences model.

1. Introduction

Despite the rapid growth of global renewable energy, energy-related CO_2 emissions hit a record high in 2024 per the IEA, with fossil fuels still dominating economic and industrial production. As a major energy consumer and carbon emitter, China highly values global climate governance and corporate carbon reduction. The 20th National Congress elevated green development and energy structure optimization to a national strategy. Relevant regulatory authorities have further stressed lowering financing barriers for corporate low-carbon transformation via green finance tools such as green bonds, aiming to build a collaborative governance framework integrating policy, market and enterprises.

In 2024, China's energy-related CO_2 emissions remained high, with electricity and heat production accounting for about 58% of total emissions, and high enterprise energy consumption being the main driver. By 2025, around 2,257 key emission entities (covering over 40% of national emissions) have been included, extending to high-emission industries. Enterprise-level carbon disclosure and accounting capabilities are uneven: most disclose Scope-1 and Scope-2 data, but less than 20% disclose Scope-3, limiting green finance effectiveness. For high-emission enterprises, short-term risks include increased operational uncertainty and costs, while long-term risks involve transformation pressure, financing constraints and weakened competitiveness; without proper enterprise-level

governance, environmental goals may be delayed with higher economic costs (Shang Wenli & Li Zhichong, 2025) [44].

Under the "dual-carbon" strategy, the Chinese government attaches great importance to green bonds and green finance as key policy tools for carbon peaking and carbon neutrality. Relevant national strategies (the 20th CPC National Congress, 14th and 15th Five-Year Plans) and documents (2025 "Green Finance Supported Project Catalogue") have emphasized and standardized the development of green finance and green bonds. Currently, China's green bond issuance scale is growing rapidly—reaching about RMB 490 billion by June 2025 with a 90% year-on-year increase, and its international influence is also strengthening, providing important capital support for enterprises' low-carbon transformation and reflecting the dual role of market vitality and policy guidance.

This paper takes green bonds as the research starting point, constructs a quasi-natural experimental framework using data of A-share listed companies in Shanghai and Shenzhen from 2010 to 2023, and employs the difference-in-differences method to identify the causal relationship between green bonds and corporate carbon emissions. It reveals the transmission paths (alleviating financing constraints, strengthening green investment, etc.) and conducts heterogeneity analysis by introducing internal corporate capabilities (digital transformation, ESG performance, etc.) and external institutional environments (industry competition, environmental regulations, etc.). The study expands green finance research and clarifies the multi-dimensional mechanisms of green bonds promoting corporate low-carbon transformation, providing new empirical evidence for relevant theoretical research and policy design.

This paper makes three marginal contributions to existing literature. First, taking corporate carbon emissions as the core research object and constructing a quasi-natural experiment based on 2010–2023 A-share listed firm data, it identifies the impact of green bonds on corporate carbon emissions and expands the environmental performance dimension of green bond research. Second, it systematically explores the underlying mechanisms via financing constraints, green investment, executive green cognition and green innovation, enriching the internal logic of green finance affecting corporate environmental behavior. Third, it integrates internal corporate characteristics and external institutional factors into a unified framework to analyze the heterogeneity of green bonds' emission reduction effects, offering empirical support for the optimization of green finance policies.

2. Literature Review

Carbon emissions represent the CO_2 released by enterprises from their operational emission sources (Gui Liangjun & Wang Nuanxin, 2025) [11]. Three mainstream measurement methods are widely adopted: first, calculating absolute carbon emissions by applying official emission factors to corporate energy consumption data such as coal, oil, gas, electricity and heat; second, adopting a life-cycle perspective to cover direct, energy-related indirect and business activity emissions to construct carbon emission level and intensity indicators; third, the industry allocation method, which estimates enterprise carbon intensity by dividing emissions by operating income and assigns industrial total emissions to individual firms based on their share of industry costs or output.

Meanwhile, Existing studies on corporate carbon emission influencing factors mainly fall into four perspectives: policy institution, technological progress, corporate governance and green finance.From policy and institutional perspective, local environmental vertical management and low-carbon city pilot policies both effectively curb corporate carbon emissions. In terms of technological progress, new quality productivity, big data pilots and green technology innovation can significantly improve corporate carbon emission efficiency. Regarding corporate governance, executive equity incentives and joint institutional investors help cut carbon emissions by mitigating management short-sightedness and optimizing operation. From green finance perspective, digital inclusive finance affects carbon intensity via scale and energy efficiency effects with an inverted U-shaped relationship; green finance pilot policies reduce emissions of heavy-polluting enterprises through funds,

technology and awareness, showing an initially strengthening then weakening trend after policy implementation.

Green bonds are securities that raise capital specifically for green projects such as environmental governance, climate response and resource conservation to support social and economic low-carbon development. Existing literature studies their economic consequences mainly from four dimensions: corporate financial performance, technological innovation, green transformation and emission reduction. Relevant findings show that green bonds can curb corporate financialization, enhance accounting robustness, drive technological competitiveness and new quality productivity, improve ESG and environmental performance, and reduce corporate marginal carbon abatement costs as well as facilitate regional carbon reduction. However, existing research lacks consistent conclusions; their actual carbon reduction effects are restricted by fund use direction, corporate absorption capacity and external supervision intensity, leaving room for further empirical exploration.

Existing studies on carbon emission measurement and green bond effects still have shortcomings. They neglect the micro transmission channels of green bonds on corporate carbon emissions, rarely explore the synergistic emission-reduction mechanisms involving corporate decision-making, green innovation quality and governance optimization, and lack in-depth heterogeneity analysis across firm traits and external environments. Against this backdrop, this paper takes corporate carbon emissions as the core variable, investigates green bonds' emission reduction effects and multidimensional mechanisms, and enriches the micro influencing paths and contextual scope of green finance policy research.

3. Theoretical Analysis and Research Hypotheses

Based on credit rationing theory, Porter's hypothesis, Schumpeter's innovation theory, and meaning-making theory, this paper constructs a theoretical framework for analyzing the impact of green bonds on corporate carbon emissions. Specifically, the four theories correspond to four pathways of action: financing constraints, green investment, green innovation, and senior management's green awareness. Green bonds can thus reduce corporate carbon emissions by alleviating financing constraints, promoting green investment, enhancing green innovation, and strengthening senior management's green awareness.

First, from the perspective of corporate financing constraints, on the one hand, green bonds reduce information asymmetry between enterprises and external investors through fund usage constraints, information disclosure and third-party certification, thereby improving the external financing environment. According to the credit rationing theory (Riley, John G , 1987) [41] , under the condition of information asymmetry, external financing entities often use quantitative rationing to allocate funds, while the clear green signal and supervision mechanism conveyed by green bonds help to alleviate adverse selection and moral hazard, thereby reducing financing constraints; on the other hand, existing studies have shown that under the effect of external supervision, the relief of financing constraints can significantly inhibit carbon emissions of industrial enterprises, and green invention patents will further strengthen this emission reduction effect (Chen Xiaobei, 2020) [33] ; the relief of financing constraints helps enterprises increase long-term investments in clean technology and energy-saving transformation, thereby reducing carbon emission levels. After the financing environment is improved, enterprises are more capable of implementing high-cost, long-recovery-period emission reduction projects and optimizing production processes and energy structures through green technology innovation.

Secondly, from the perspective of corporate green investment, on the one hand, green bonds can alleviate the financial constraints of enterprises on green projects by providing special low-cost and maturity-matched funding sources, thereby improving the level of green investment. According to Porter's hypothesis (Wang Guoyin, Wang Dong, 2011) [47] , reasonable environmental investment can incentivize enterprises to optimize resource allocation and improve production efficiency, while the environmental constraints and incentive mechanisms attached to green bonds can help guide enterprises to invest funds in green investment areas such as energy conservation and emission

reduction and clean production; on the other hand, the increase in corporate green investment can directly reduce the carbon emission level per unit output by improving the energy structure, improving energy utilization efficiency and optimizing production processes. Related studies have shown that the development of green finance, especially the expansion of green credit, green industry investment and green bonds, can significantly suppress regional carbon emission intensity (You Zhiting et al., 2022) [30] .

Furthermore, from the perspective of corporate green innovation, green bonds supply stable long-term dedicated green funds, lowering uncertainties in green R&D and stimulating green technological innovation. Based on innovation theory, green bonds channel capital into clean and energy-saving technologies, enabling firms to advance low-carbon R&D and enhance green innovation capacity. In turn, improved green innovation cuts carbon emissions by boosting energy efficiency, optimizing production processes and promoting low-carbon technology substitution. Though its emission reduction effect is constrained by energy intensity and other factors, green technological progress overall significantly raises carbon emission efficiency and achieves emission abatement.

From the perspective of executives' green awareness, green bonds embed low-carbon goals into corporate financing and governance via fund usage constraints, third-party certification and mandatory information disclosure. Based on meaning-building theory, external institutional signals from green bonds reshape executives' environmental cognition, raising their focus on green development and integrating low-carbon targets into corporate strategy. Meanwhile, enhanced green awareness motivates executives to advance green innovation, optimize production processes and energy management, and rationalize resource allocation, thereby improving environmental performance and cutting carbon emissions. Existing literature also confirms that executive environmental cognition boosts ESG performance and facilitates corporate emission reduction through green innovation.

In summary, this paper proposes Hypothesis 1 and Hypothesis 2:

H1: Green bonds can reduce corporate carbon emissions.

H2: Green bonds can reduce corporate carbon emissions by lowering corporate financing constraints, increasing corporate green investment, enhancing corporate green innovation, and raising executives' green awareness.

4. Research Design

4.1. Model Setup

4.1.1. Benchmark Regression Model

To examine the impact of green bonds on corporate carbon emissions , the following regression model is constructed:

$$TPF=\alpha_0+\alpha_1 \text{inter}_{it}+\alpha_2 Control_{it}+\delta_i+\rho_t+\varepsilon_{it} \quad (1)$$

In the above formula, i represents the firm, t represents the year, the dependent variable is firm carbon emissions, the explanatory variable is green bonds, $Control_{it}$ and the relevant control variables are . δ_i represents the firm fixed effect, ρ_t represents the time effect, ε_{it} and is a random disturbance term.

4.1.2. Mediation Effect Model

To explore the mechanism of green bonds' impact on corporate carbon emissions , this paper adopts the mediation effect analysis method. Given that the traditional stepwise regression method for mediation effects has the problem of endogeneity estimation bias (Jiang Ting, 2022) [30] , this paper examines the impact of the core explanatory variable on the mediation variable by replacing the explanatory variable with the mediating variable, so as to test the existence and effectiveness of the mediating path. The mediation effect model is set as follows:

$$M=\partial_0+\partial_1 inter_{it}+\partial_2 Control_{it}+\delta_i+\rho_t+\varepsilon_{it} \quad (2)$$

MThe mediating variables include financing constraints, executives' green awareness, corporate green investment, quantity of green innovation and quality of green innovation, and the remaining variables are consistent with equation (1).

4.2. Variable Selection

4.2.1. Explained Variable

Corporate Carbon Emissions (CE): Referring to the research of Wang Hao et al., this study first calculates the total annual carbon emissions of enterprises, specifically including emissions from energy combustion and escape, emissions from production processes, emissions from waste disposal, and carbon emissions caused by changes in land use patterns (such as converting forests to industrial land). Based on this, to eliminate the impact of differences in enterprise size on the measurement results, a carbon emission intensity index is further constructed using the ratio of total corporate carbon emissions to operating revenue, to characterize the carbon emission level corresponding to each unit of enterprise output.

4.2.2. Explanatory Variables

Green bonds (GB): This is the dependent variable. It is an interaction of whether a company issues green bonds (Treat) and a dummy variable indicating the timing of policy implementation (Post), i.e., GB = Treat × Post. Treat distinguishes the experimental and control groups: companies that have issued green bonds receive a value of 1, while other companies receive a value of 0. Post is a time dummy variable, assigned a value of 1 for the year the green bond policy was implemented and subsequent years, and a value of 0 for other years.

4.2.3. Mediating Variables

Financing constraints (FC): Financing constraints are measured using the WW index. This index is constructed based on the theory of financial distress prediction and financing constraints. By integrating multiple financial indicators, it comprehensively describes the degree of external financing restrictions faced by enterprises. It can reflect the financing pressure faced by enterprises in a relatively comprehensive way, and therefore has been widely used in related studies. (Liu Mengxin, Du Wei , 2025) [12]

Corporate green investment refers to capital and R&D spending by enterprises on energy conservation, emission reduction, pollution control, resource recycling and ecological protection, reflecting their strategic commitment to green technologies and clean energy (Li Tao & Li Ang, 2019) [31]. For measurement, this study sums expenditures on environmental protection projects including desulfurization, sewage treatment, waste gas management, clean technology innovation and green equipment procurement. To eliminate firm size differences, total green investment is divided by period-end total assets to construct green investment intensity (Zhang Qi et al., 2019) [34], which effectively reflects enterprises' actual capital input scale for green transformation.

Green innovation quantity (Gin): Green innovation is a technological innovation behavior aimed at resource conservation and pollution reduction, covering hardware innovation such as environmental protection equipment and clean production technology, as well as software innovation such as green management processes and operation strategies. In order to measure the activity and innovation output of enterprises in green technology research and development, the number of green patent applications is often used as a proxy variable (Shi Sheng & Zhang Ya, 2024) [20] . This indicator can reflect the R&D funds, human resources and time costs invested by enterprises in the field of green technology, as well as their ability to transform R&D activities into patentable technological achievements. The more green patent applications, the higher the sustainability and output efficiency of the enterprise's green innovation activities.

Green innovation quality (Giq): Green innovation quality emphasizes the influence and value realization capability of green technology innovation. This paper uses the number of times green patents are cited as the measurement basis. The more times a patent is cited, the stronger the knowledge spillover effect of the technology in the industry, and the higher its technological advancement and potential market value. This indicator reflects the substantive contribution and technological level of the company's green innovation activities from the perspective of the impact of the results (Tao Feng et al., 2025) [10] .

This paper adopts text analysis of listed firms' annual reports to measure executives' green cognition. It establishes a keyword system covering green competitive advantage, corporate social responsibility and external environmental pressure, including terms related to energy conservation, environmental protection strategies, governance, technology and supervision. The executive green cognition index is constructed by counting the word frequency of these keywords in annual reports to reflect management's attention to environmental issues. Given the consistent connotation between executives' environmental and green cognition, this study makes no distinction between them. The final indicator is defined as the ratio of green cognition keyword occurrences to the total word count of annual reports (Li Yabing et al., 2022) [28].

4.2.4. Control Variables

Based on previous research, the following variables that may affect corporate carbon emissions were selected: Firm size (Size): represented by the logarithm of the firm's total assets at year-end; Top 1 shareholder shareholding ratio (Top1): represented by the largest shareholder's shareholding divided by the company's total share capital; Debt-to-equity ratio (Lev): represented by the firm's total liabilities at year-end divided by its total assets at year-end; Return on total assets (Roa): represented by net profit divided by total assets; Cash holdings (Cash): represented by net cash flow from operating activities divided by total assets; Gross Domestic Product (GDP): Ln (city GDP); Regional industrial upgrading (Upgrade): represented by the added value of the tertiary industry divided by the added value of the secondary industry; Whether the firm has a dual role (Dual): 1 if the chairman and general manager are the same person, 0 otherwise; Board size (Board) : measured by the number of board members.

4.3. Data Sources and Processing

This paper uses A-share listed companies from 2010 to 2023 as the research sample, removes missing samples, and performs 1% tail reduction on all data, ultimately obtaining 31,133 observations. The main explanatory variable, the list of green bonds, is from the Guotai An database ; enterprise-level data is from WIND and Guotai An CSMAR databases; and city-level data is from the "City Statistical Yearbook". Data processing and regression analysis were performed using Stata 18.0. Descriptive statistics of the variables are detailed in Table 1 .

Table 1. Descriptive Statistics

VarName	Obs	Mean	SD	Min	Median	Max
CE	31133	2.8121	0.9151	0.4237	3.1031	4.0759
GB	31133	0.1931	0.3948	0.0000	0.0000	1.0000
Roa	31133	0.0462	0.0926	-1.1376	0.0420	10.0322
Size	31133	22.2682	1.3655	17.6413	22.0355	28.6969
Lev	31133	0.4145	0.2068	0.0075	0.4066	2.8409
Top1	31133	0.3474	0.1494	0.0029	0.3269	0.8999
Board	31133	2.1254	0.1975	1.3863	2.1972	2.9444
Cash	31133	0.2552	0.4073	-0.5500	0.1609	2.1323
Dual	31133	0.2923	0.4548	0.0000	0.0000	1.0000
GDP	31133	10.6428	0.8003	6.2400	10.7102	11.8180
Upgrade	31133	2.4734	0.1385	2.1323	2.4515	2.8461

5. Empirical Results

5.1. Benchmark Regression Results

Table 2 reports the baseline regression results of green bond policies on corporate carbon emissions. Column (1) is the regression model without control variables, and columns (2) to (5) are the regression settings for variable year and individual, year-only fixed effect, individual-only fixed effect, and two-way fixed effect of year and individual, respectively. The results show that the regression results of columns (1) to (5) are all negatively significant. The regression coefficient of the core explanatory variable, green bonds (GB), in column (5) is -0.0355 , which is significant at the 1% level. This indicates that green bond policies can significantly suppress corporate carbon emissions.

Table 2. Benchmark Regression Results

	(1)	(2)	(3)	(4)	(5)
	CE	CE	CE	CE	CE
GB	-0.0362***	-1.4104***	-0.0410***	-1.4393***	-0.0355***
	(-3.673)	(-133.469)	(-5.249)	(-109.761)	(-3.605)
Roa		0.0775*	-0.1475***	-0.0693	-0.1740***
		(1.654)	(-5.919)	(-1.388)	(-6.211)
Size		-0.0191***	0.0069***	-0.0384***	0.0115**
		(-5.187)	(3.505)	(-3.791)	(2.014)
Leo		0.0013	-0.0456***	-0.1843***	-0.1030***
		(0.050)	(-3.335)	(-4.622)	(-4.596)
Top1		0.1658***	0.0219	0.0653	0.0367
		(5,999)	(1,482)	(0.986)	(0.986)
Board		0.1134***	-0.0186	-0.0151	-0.0257
		(5.265)	(-1.615)	(-0.387)	(-1.170)
Cash		-0.0058	0.0065	0.0515***	0.0227***
		(-0.507)	(1.073)	(3.620)	(2.844)
Dual		-0.0006	-0.0016	0.0241*	0.0024
		(-0.061)	(-0.330)	(1.741)	(0.303)
GDP		-0.0790***	0.0066**	-1.0644***	-0.0292
		(-14.779)	(2.176)	(-34.870)	(-0.619)
Upgrade		-0.0999***	0.0119	4.5129***	0.0109
		(-3.307)	(0.720)	(26.932)	(0.087)
_cons	3.2300***	4.2977***	3.0498***	4.1800***	3.3336***
	(307.820)	(38.168)	(48.333)	(15.503)	(5.379)
FE	Yes	No	No	Yes	Yes
Year	Yes	No	Yes	No	Yes
N	31133	31133	31133	31133	31133
R^2	0.8531	0.4091	0.8347	0.5308	0.8535

Note: ***, **, and * represent significance levels of 1%, 5%, and 10%, respectively. The same applies to the following table.

5.2. Parallel Trend Test

The effectiveness of the difference-in-differences model depends on the satisfaction of the parallel trend assumption, i.e., before policy intervention, the outcome variables of the experimental group and the control group should show similar trends; otherwise, it may lead to biased estimation of the policy effect. To maintain the simplicity of the regression results and avoid estimation bias, the periods before and after the time treatment are merged. Considering the limited data for the previous 5 years, this paper summarizes the data for the 5 years before the issuance of green bonds into the 5th year before the issuance of green bonds , and after merging , $n \in [-5, 4]$. To avoid multicollinearity

and to intuitively show the changes in corporate carbon emissions before and after the treatment, this paper chooses the period before the treatment (period -1) as the base period.

As shown in the figure, at each observation point before policy intervention (5 to 2 years before issuance), the TPF coefficients of both the experimental and control groups fluctuated slightly around 0, and the corresponding confidence intervals all included 0, indicating that there was no significant difference in the carbon emission change trends between the two groups of enterprises, and the parallel trend hypothesis was valid. However, after the policy was implemented (1 year and beyond), the TPF coefficients changed significantly, indicating that the policy had a significant inhibitory effect on corporate carbon emissions.

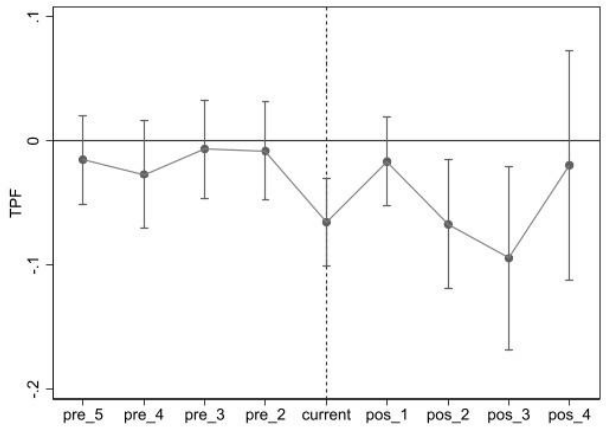

Figure 1. TPF Parallel Trend Test

5.3. Heterogeneity Treatment Effect Test

Given that green bond policies are implemented in batches at the corporate level, the multi-period difference-in-differences (TWFE) estimation may produce weighting bias when there is heterogeneity in treatment effects. To test the identification validity of the benchmark results, this paper decomposes the TWFE estimation according to Andrew (2021) [45] and draws a 2×2 DID weight-estimate distribution diagram (see Figure 2).

As can be observed from the figure, the estimated values for all types of 2×2 comparisons are generally concentrated in the negative range, and no systematic reversal of direction is observed; the overall estimated value (dashed line) is approximately −0.037, which is highly consistent with the baseline regression results. Further examination of the weight structure reveals that the comparison between the "treated group and the untreated group" accounts for the majority of the weights, exceeding 60%, while the weights corresponding to "comparisons between treated groups" are smaller and do not exhibit significantly negative weights or abnormally deviated estimated values. Most weights are distributed in the lower range, and no single high-weighted comparison dominates the overall estimate.

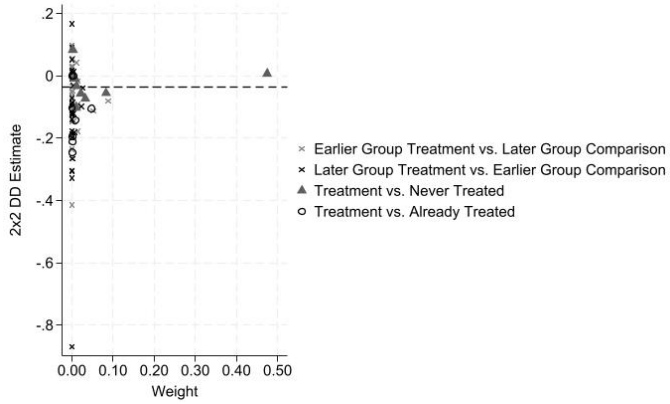

Figure 2. Decomposition diagram of bacon

The above results indicate that the TWFE estimation in this paper did not suffer from significant weighting distortion due to the batch treatment structure, and the baseline estimate mainly came from the comparison with the effective control group. Based on this, this paper further employs a more robust multi-period DID identification method to re-estimate the treatment effect, and the results remain consistent in direction, significance, and order of magnitude. Combining the weight decomposition and alternative estimation results, it can be confirmed that the inhibitory effect of green bonds on corporate carbon emissions is not driven by heterogeneous treatment structures or weight bias, thereby enhancing the reliability of the core conclusions and the robustness of the econometrics.

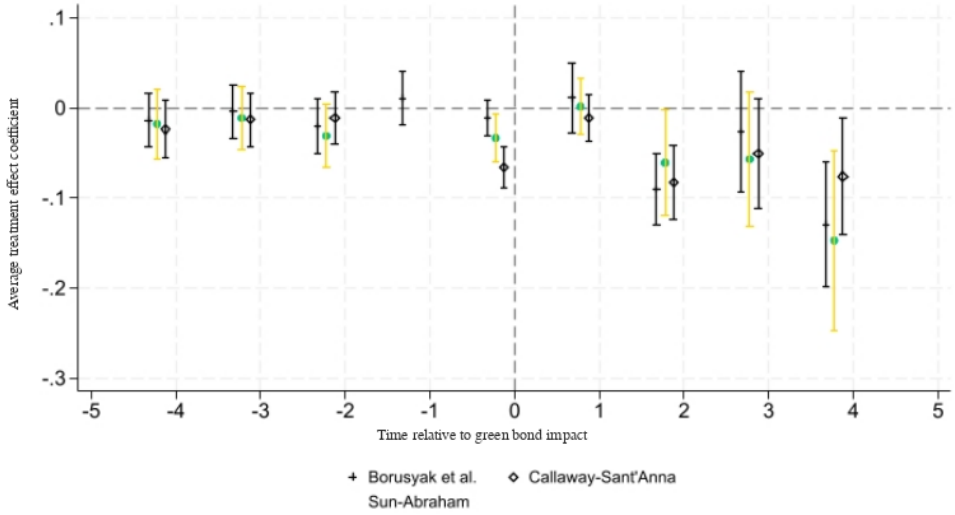

Figure 3. Dynamic treatment effect (TPF) of three types of DID estimators

5.4. Placebo Test

To rule out omitted variables and unobservable shocks, this paper conducts a randomized placebo test to verify the identification validity of green bond policies under the multi-period DID framework. It randomly selects fictitious treatment firms and policy timing, constructs virtual interaction terms, and repeats the randomization 500 times for regression estimation. As shown in Figure 4, the randomized coefficients cluster around zero and lie mostly to the right of the true estimate of −0.0355, with greatly weakened policy significance. The results confirm that the documented carbon reduction effect is not caused by random interference or unobserved shocks, further verifying the robustness of the baseline findings.

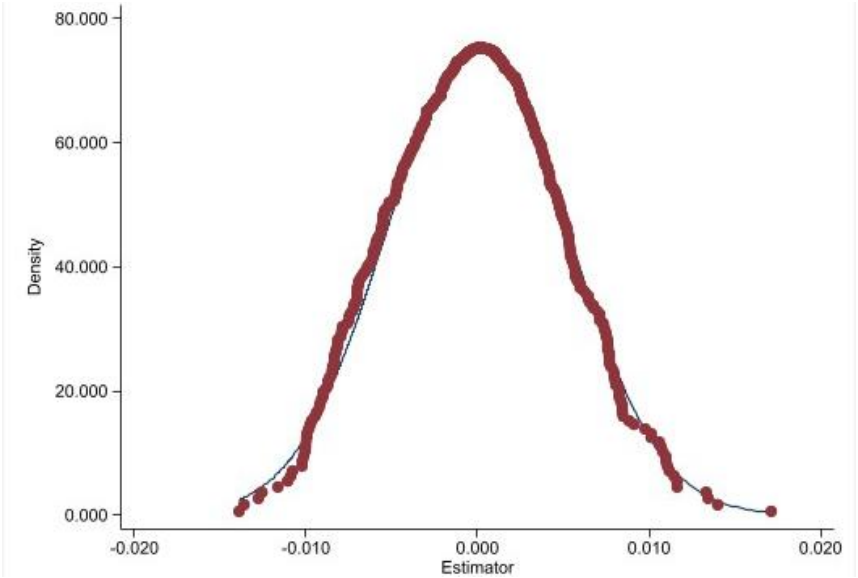

Figure 4. Placebo test for TPF

6. Propensity Score and Robustness Test

6.1. Propensity Score Matching Method

To mitigate the potential interference of sample selection bias on the baseline regression results, this paper employs propensity score matching (PSM) for robustness testing, further verifying the robustness of the impact of green bond policies on corporate carbon emissions. Specifically, this paper constructs a matching sample based on the basic characteristic variables of enterprises, and uses a 1:3 nearest neighbor matching method to re-pair enterprises included in the pilot area with those not included, and then performs regression estimation on the matched samples. Table 3 reports the regression results after propensity score matching. Columns (1) and (2) show that the regression coefficients of the policy variable GB on corporate carbon emissions are -0.0406 and -0.0407, respectively, both significant at the 1% significance level. In summary, this indicates that after controlling for sample selection bias, green bonds still have a significant inhibitory effect on corporate carbon emissions, thus further verifying the robustness of the baseline regression results.

Table 3. Propensity Match Scores

	(1)	(2)
	CE	CE
GB	-0.0406***	-0.0407***
	(-3.130)	(-3.139)
Roa		-0.0140
		(-0.226)
Size		0.0162*
		(1.677)
Lev		-0.0669*
		(-1.787)
Top1		-0.0337
		(-0.532)
Board		-0.0784**
		(-2.284)
Cash		0.0178
		(1.461)
Dual		-0.0040
		(-0.342)
GDP		-0.1782*
		(-1.694)
Upgrade		-0.0578
		(-0.240)
_cons	3.2638***	5.0577***
	(126.848)	(3.835)
FE	Yes	Yes
Year	Yes	Yes
N	16203	16203
R^2	0.8980	0.8981

6.2. Excluding the impact of national-level big data policies

To make the research results more robust, this paper also examines the validation effect by removing the influence of the national-level big data comprehensive pilot zone policy. According to the regression results in column (1) of Table 3 , the regression coefficient of the core explanatory variable GB is -0.0360 , which is significant at the 1% significance level. This shows that the regression test results after removing the influence of the national-level big data comprehensive pilot zone policy are consistent with the baseline regression, indicating the robustness of the regression results.

6.3. Excluding the impact of the epidemic

To further verify the robustness of the baseline regression results, this paper considers that the COVID-19 pandemic, as a sudden external shock, may interfere with corporate carbon emissions and the effectiveness of policy implementation. Therefore, the 2020 sample was excluded to control for the impact of pandemic intervention factors. The regression results in column (2) of Table 3 show that the regression coefficient of the core explanatory variable is -0.0262 , which is significant at the 5% significance level, indicating that the inhibitory effect of green bonds on corporate carbon emissions still exists after excluding the pandemic year.

6.4. Adding Control Variables

To further control for potential confounding factors related to corporate governance structure and operating conditions, this paper introduces corporate age (AGE) and corporate growth (GROWTH) as additional control variables in the regression. According to the regression results in Table 4 (3), the regression coefficient of the core explanatory variable GB is -0.0360 , and it is significant at the 1% significance level. This indicates that the effect of green bonds on corporate carbon emissions remains robust.

Table 4. Robustness Tests

	Excluding the policy of national-level big data comprehensive pilot zones	Excluding major events - the 2020 pandemic	Add control variables
	CE	CE	CE
GB	-0.0360***	-0.0262**	-0.0360***
	(-3.627)	(-2.480)	(-3.653)
R oa	-0.1670***	-0.1832***	-0.1689***
	(-5.924)	(-6.344)	(-6.018)
Size	0.0106*	0.0107*	0.0103*
	(1.829)	(1.807)	(1.789)
L ev	-0.0934***	-0.1104***	-0.1132***
	(-4.112)	(-4.754)	(-4.894)
Top op1	0.0477	0.0179	0.0494
	(1.264)	(0.464)	(1.302)
Board	-0.0305	-0.0354	-0.0229
	(-1.383)	(-1.548)	(-1.044)
Cash	0.0217***	0.0253***	0.0229***
	(2.700)	(3.014)	(2.871)
Dual	0.0034	0.0019	0.0028
	(0.437)	(0.230)	(0.361)
GDP	-0.0250	-0.0138	-0.0308
	(-0.522)	(-0.283)	(-0.655)
Upgrade	-0.0225	0.0408	0.0074
	(-0.172)	(0.316)	(0.059)
GB2	-0.0079		
	(-0.750)		
GROWTH			-0.0016***
			(-4.161)
AGE			0.0143*
			(1.956)
_ cons	3.3957***	3.1599***	3.3618***
	(5.317)	(4.931)	(5.425)
FE	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	30745	28387	31133
R^2	0.8540	0.8630	0.8536

6.5. Endogeneity Test

Table 5. Endogeneity test

	Sewage discharge fee/environmental protection tax payable	Actual payment of sewage discharge fees/environmental protection taxes
	TPF	TPF
GB	-3.11611***	-3.11963***
	(-7.125)	(-7.139)
ROA	-0.33259*	-0.33383*
	(-1.870)	(-1.878)
SIZE	0.04326***	0.04338***
	(2.618)	(2.628)
LEV	-0.06105	-0.06130
	(-1.269)	(-1.275)
TOP	-0.10914	-0.10966
	(-1.435)	(-1.443)
MBOARD	-0.07535	-0.07575
	(-1.294)	(-1.302)
CASH	0.04523*	0.04537*
	(1.877)	(1.883)
DUAL	0.03960**	0.03969**
	(2.217)	(2.222)
GDP	0.09608**	0.09646**
	(2.022)	(2.032)
CYJG	0.26390**	0.26469**
	(2.492)	(2.501)
_ cons	0.98536	0.97842
	(1.124)	(1.117)
FE	Yes	Yes
Year	Yes	Yes
N	29363	29363
R^2	/	/

While the difference-in-differences model can mitigate the bias of omitted variables to some extent, it may still introduce reverse causality or unobservable shocks that could affect the estimation results. Specifically, companies with higher carbon emission levels may be more inclined to issue green bonds to improve their environmental image or reduce compliance risks, thus potentially affecting the estimation results with endogeneity. To further enhance the reliability of the identification, this paper uses alternative environmental cost indicators to test for endogeneity.

Specifically, regression estimation was performed again using "payable pollution discharge fees/environmental protection taxes" and "actually paid pollution discharge fees/environmental protection taxes" as instrumental variables. This indicator can characterize changes in corporate environmental behavior from the perspective of actual environmental governance costs, possessing strong objectivity and external constraint characteristics. The regression results are shown in Table 5. The coefficients of the core explanatory variable GB are -3.1161 and -3.1196, respectively, both significant at the 1% significance level, and their directions are consistent with the baseline regression. In conclusion, after controlling for potential endogeneity issues using the instrumental variable method, the core conclusions of this study remain robust.

7. Mediation Effect Analysis

7.1. The Mediating Role of Financing Constraints (FC)

Column (1) of Table 6 shows that the coefficient of influence of green bonds on financing constraints is -0.0153, which is significant at the 5% significance level, indicating that green bonds can reduce corporate financing constraints. At the same time, financing constraints will significantly inhibit enterprises' continuous investment in energy conservation, emission reduction and environmental governance, and will exacerbate enterprises' dependence on high-carbon production paths by restricting the introduction of clean technologies and green R&D activities, thereby increasing carbon emission levels. Chen Xiaobei et al. (2021) [33] found that the stronger the financing constraints of enterprises, the weaker their emission reduction capacity and the more difficult it is to achieve low-carbon transformation through technological innovation. Improved financing environment can significantly reduce carbon emissions of industrial enterprises. Therefore, financing constraints play an important transmission role between green bonds and corporate carbon emissions, verifying the existence of the mediating effect.

7.2. The Mediating Role of Green Investing

Column (2) of Table 6 shows that the impact coefficient of green bonds on green investment is 0.0038, which is significant at the 10% significance level, indicating that green bonds can increase corporate green investment. In addition, existing studies have shown that green industry investment can significantly suppress carbon emissions by guiding funds to environmental protection and clean technology industries, promoting industrial structure optimization and technological progress. Yu Zhiting et al. (2022) [30] further found, based on empirical results of provincial panel data, that green industry investment has a significant negative impact on regional carbon emissions and forms a complementary effect with other green financial instruments, continuously amplifying the emission reduction effect. Therefore, green investment plays an important transmission role between green bonds and corporate carbon emissions, verifying the existence of the mediating effect.

Table 6. Mediation effect regression

	(1)	(2)	(3)	(4)	(5)
	FC	GreenInvest	Gin	Giq	GreenCog
GB	-0.0153**	0.0038*	0.0443***	0.0274*	0.0004***
	(-2.234)	(1.946)	(2.760)	(1.959)	(3.570)
Roa	-0.0907***	-0.0902***	-0.0560	-0.1421***	0.0015***
	(-3.241)	(-18.737)	(-1.225)	(-3.585)	(3.123)
Size	-0.1202***	-0.0327***	0.3208***	0.1649***	0.0000
	(-30.309)	(-31.205)	(34.339)	(20.268)	(0.223)
Lev	-0.1815***	-0.0128***	-0.1113***	0.1532***	-0.0009***
	(-11.442)	(-3.162)	(-3.047)	(4.833)	(-3.305)
Top1	-0.0324	-0.0253***	0.0940	-0.2351***	-0.0010**
	(-1.265)	(-3.750)	(1.549)	(-4.462)	(-2.414)
Rroad	0.0131	-0.0045	0.0239	0.0053	-0.0005*
	(0.869)	(-1.130)	(0.669)	(0.172)	(-1.884)
Cash	0.0024	-0.0165***	0.0047	0.0096	0.0001
	(0.438)	(-11.506)	(0.363)	(0.852)	(1.199)
Dual	0.0043	-0.0006	0.0378***	0.0027	-0.0002**
	(0.804)	(-0.440)	(2.991)	(0.247)	(-2.285)
GDP	0.0136	0.0109	0.0860	0.2196***	0.0019***
	(0.418)	(1.278)	(1.121)	(3.297)	(3.595)
Upgrade	-0.1364	-0.0288	-0.6494***	-0.3854**	0.0044***
	(-1.579)	(-1.247)	(-3.177)	(-2.167)	(3.169)
_cons	1.9123***	0.8634***	-6.1023***	-4.7554***	-0.0227***
	(4.473)	(7.662)	(-6.040)	(-5.420)	(-3.316)
FE	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
N	30988	27640	31133	30858	30112
R^2	0.5338	0.7250	0.7148	0.7563	0.6343

7.3. Intermediary between the quantity and quality of green innovation

In Table 6, green bonds significantly boost both the quantity (coefficient 0.0443, 1% level) and quality (coefficient 0.0274, 10% level) of corporate green innovation. Green innovation further enhances firms' carbon performance by advancing energy-saving technologies and clean production, improving energy efficiency and lowering emission intensity. Consistent with existing research, green innovation serves as a key endogenous driver of corporate low-carbon transformation.

Therefore, the quantity and quality of green innovations play an important role in the transmission between green bonds and corporate carbon emissions, verifying the existence of the mediating effect.

7.4. Senior Management's Green Awareness Intermediary

In column (5) of Table 6 , the impact coefficient of green bonds on executives' green awareness is 0.0004 , which is significant at the 1% significance level, indicating that green bonds can improve executives' green awareness.

At the same time, executives' green awareness can not only strengthen the company's ability to identify environmental risks, but also improve the company's environmental governance by reducing management short-sightedness, promoting green innovation and digital transformation, thereby effectively improving the company's carbon management capabilities. (Zhou et al., 2025) [42] further pointed out that executives' green awareness can prompt companies to invest more resources in low-carbon strategies, carbon emission management and environmental information disclosure, making companies more inclined to take substantial emission reduction actions, and ultimately significantly

improve carbon performance. Therefore, executives' green awareness and corporate carbon emissions play an important transmission role, verifying the existence of the mediating effect.

8. Heterogeneity Analysis

Based on the technology-organization-environment (TOE) analysis framework, this section empirically examines the impact of green bonds on corporate carbon emissions, and focuses on the moderating effects of technology, organization, and environment.

8.1. Technical Capabilities

Technological capability refers to the ability of a company's management and employees to utilize various types of technological resources. In the TOE framework, the technology dimension focuses on the company's intrinsic technological capabilities.

Higher corporate digitalization strengthens data integration, information processing and process visualization, improving resource allocation and environmental risk identification. It enables firms to better convert green bond financial advantages into energy-saving renovation, clean production and green technology upgrades, amplifying the policy's emission reduction effect (Liu Hongduo et al., 2023) [26]. A larger share of highly skilled personnel enhances enterprises' capacity for technology absorption and green innovation, allowing green bond funds to more effectively drive green innovation and emission abatement (Chen Yifei et al., 2025) [7]. This paper predicts that green bonds exert a stronger carbon suppression effect in enterprises with advanced digital transformation and abundant high-skilled talent.

First, this paper, referencing the research of scholars such as Wu Fei, defines enterprise digital transformation indicators as core measurement indicators to characterize the synergistic interaction effect between technological capabilities and green data center pilot policies. The heterogeneity of digital transformation is shown in column (2) of Table 7. The results show that the impact coefficient of green bond policies on carbon emissions is -0.0409, which is significant at the 1% significance level. The impact coefficient of DCG_GB is -0.0101, both of which are significant at the 10% significance level, indicating that enterprises with higher levels of digital transformation have a stronger effect on inhibiting carbon emissions through green bond policies.

Secondly, this paper, referencing the research methods of scholars such as Liu Qiren, uses the ratio of highly skilled personnel to the total number of employees to measure the heterogeneity of the proportion of highly skilled personnel in enterprises. The results of the heterogeneity of the proportion of highly skilled personnel are shown in column (3) of Table 7. The results show that the impact coefficient of green bond policy on carbon emissions is -0.0459, which is significant at the 1% significance level. The impact coefficient of GJSRY_GB is -0.1111, which is significant at the 5% significance level. This indicates that enterprises with a higher proportion of highly skilled personnel have a stronger carbon emission suppression effect from green bond policy.

Table 7. Technological capability heterogeneity

	(1)	Digital transformation level	High-tech personnel ratio
	CE	CE	CE
GB	-0.0355***	-0.0409***	-0.0459***
	(-3.605)	(-3.856)	(-4.343)
Roa	-0.1740***	-0.1755***	-0.1661***
	(-6.211)	(-6.284)	(-5.825)
Size	0.0115**	0.0085	0.0163**
	(2.014)	(1.446)	(2.529)
Lev	-0.1030***	-0.1040***	-0.1034***
	(-4.596)	(-4.541)	(-4.188)
Top1	0.0367	0.0631*	0.0287
	(0.986)	(1.681)	(0.705)
Board	-0.0257	-0.0193	-0.0345
	(-1.170)	(-0.864)	(-1.456)
Cash	0.0227***	0.0225***	0.0304***
	(2.844)	(2.668)	(3.386)
Dual	0.0024	0.0078	0.0093
	(0.303)	(0.975)	(1.112)
GDP	-0.0292	-0.0223	-0.0037
	(-0.619)	(−0.466)	(−0.068)
Upgrade	0.0109	-0.1143	-0.1497
	(0.087)	(−0.897)	(-1.051)
DCG		0.0002	
		(0.047)	
DCG GB		-0.0101*	
		(-1.863)	
GJSRY			0.0038
			(0.117)
GJSRY GB			-0.1111**
			(-2,150)
cons	3.3336***	3.6115***	3.3706***
	(5,379)	(5,732)	(4,684)
FE	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	31133	29081	26687
R^2	0.8535	0.8629	0.8711

8.2. Organizational Capability

Organizational capability refers to an enterprise's ability to integrate resources and coordinate cooperation to achieve strategic goals. In the TOE framework, the organizational dimension focuses on internal management efficiency. Higher enterprise digitalization enhances information processing, resource allocation and environmental risk identification capabilities, helping transform green bonds' financial advantages into low-carbon investments and amplify their emission reduction effect. Enterprises with stronger risk-bearing capacity are more forward-looking, inclined to use green bond funds for high-investment, long-payback green transformation projects (Yu Weina et al., 2016) [39]. Companies with higher ESG ratings have sound environmental constraint mechanisms, efficiently allocating green bond funds to emission-reducing projects and improving policy transmission efficiency (Qiu Muyuan & Yin Hong, 2019) [36]. This paper predicts that green bonds have a stronger carbon emission inhibition effect on enterprises with high risk-taking levels and high ESG ratings.

First , this paper uses stock return volatility to measure risk-taking level, which can more accurately reflect corporate risk-taking behavior than financial indicators. This paper refers to the research method of Su Kun (2016) [45] and uses the logarithmic value of annualized daily return standard deviation (CRT) to measure it. The results are shown in column (2) of Table 8. The impact coefficient

of green bond policy on carbon emissions is -0.0313, which is significant at the 1% significance level. The impact coefficient of CRT_GB is -0.0412, which is significant at the 10% significance level. This indicates that the higher the corporate risk-taking level, the stronger the effect of green bonds on corporate carbon emissions.

Furthermore , this paper uses Huazheng ESG rating to measure corporate ESG scores. The results are shown in column (3) of Table 8. The impact coefficient of green bonds on carbon emissions is -0.0358, which is significant at the 1% significance level. The impact coefficient of ESG_GB is -0.2281, both of which are significant at the 5% significance level. This indicates that the higher the corporate ESG score, the stronger the effect of green bond policies on corporate carbon emissions.

Table 8. Organizational heterogeneity

	(1)	Risk tolerance level	ESG
	CE	CE	CE
GB	-0.0355***	-0.0313***	-0.0358***
	(-3.605)	(-2.943)	(-3.560)
Roa	-0.1740***	-0.1332***	-0.1751***
	(-6.211)	(-3.260)	(-6.282)
Size	0.0115**	0.0095*	0.0098*
	(2.014)	(1.650)	(1.694)
Lev	-0.1030***	-0.0966***	-0.1038***
	(-4.596)	(-4.187)	(-4.584)
Top1	0.0367	0.0512	0.0410
	(0.986)	(1.378)	(1.108)
Board	-0.0257	-0.0231	-0.0270
	(-1.170)	(-1.054)	(-1.234)
Cash	0.0227***	0.0202**	0.0210***
	(2.844)	(2.490)	(2.634)
Dual	0.0024	0.0029	0.0047
	(0.303)	(0.375)	(0.606)
GDP	-0.0292	-0.0236	-0.0205
	(-0.619)	(-0.504)	(-0.437)
Upgrade	0.0109	-0.0196	-0.0293
	(0.087)	(-0.156)	(-0.234)
CRT		0.0007	
		(0.083)	
CRT_GB		-0.0412*	
		(-1.942)	
ESG			-0.0318
			(-0.708)
ESG_GB			-0.2281**
			(-1.975)
_cons	3.3336***	3.3795***	3.5154***
	(5.379)	(5.471)	(5.450)
FE	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	31133	30439	30550
R^2	0.8535	0.8566	0.8573

8.3. External Environment

The external policy and market environment shapes firms' carbon reduction incentives. Intensified industry competition raises cost pressures, driving enterprises to pursue differentiated competitive edges via green innovation. Such firms tend to deploy green bond funds faster into energy-saving renovation and process optimization, amplifying the policy emission reduction effect. Stricter regional environmental regulations push firms to proactively adjust operational and governance strategies, and allocate green bond capital more precisely to pollution control and clean production

projects. This paper predicts that green bonds exert a stronger carbon emission suppression effect for enterprises located in regions with higher industry competition and stricter environmental regulations.

First, the Herfindahl index is used to measure industry concentration, which is obtained by calculating the sum of squares of the market share of each enterprise in the industry (Liu Guanchun et al., 2021) [32] . The higher the index value, the higher the industry concentration and the lower the degree of competition. The results are shown in column (2) of Table 9. The impact coefficient of green bond policy on carbon emissions is -0.0394, which is significant at the 1% significance level. The impact coefficient of HHI_GB is -0.1145, which is significant at the 5% significance level. This indicates that the higher the level of regional industry competition, the stronger the effect of green bond policy on the carbon emission suppression of enterprises.

Secondly, environmental regulations, as external institutional constraints, raise firms' compliance pressure and drive green transformation and technological upgrading (Zhu Pingfang et al., 2011) [40]. This study measures regional environmental regulation intensity by calculating the proportion of environmental protection-related keywords in local government work reports, following Chen Shiyi and Chen Dengke (2018) [46]. According to Table 9 Column (3), the green bond policy coefficient on carbon emissions is −0.0403 (1% significance), and the interaction term coefficient is −0.0563 (5% significance). The results suggest that stricter regional environmental regulations significantly strengthen the carbon emission reduction effect of green bonds.

Table 9. Heterogeneity of the external environment

	(1)	Industry competition level	Regional environmental regulation level
	CE	CE	CE
GB	-0.0355***	-0.0394***	-0.0403***
	(-3.605)	(-3.965)	(-4.045)
Roa	-0.1740***	-0.1748***	-0.1800***
	(-6.211)	(-6.237)	(-6.432)
Size	0.0115**	0.0114**	0.0112*
	(2.014)	(1.982)	(1.951)
Lev	-0.1030***	-0.1025***	-0.1095***
	(-4.596)	(-4.568)	(-4.885)
Top1	0.0367	0.0359	0.0317
	(0.986)	(0.963)	(0.853)
Board	-0.0257	-0.0257	-0.0298
	(-1.170)	(-1.169)	(-1.361)
Cash	0.0227***	0.0229***	0.0237***
	(2.844)	(2.863)	(2.973)
Dual	0.0024	0.0024	0.0032
	(0.303)	(0.309)	(0.407)
GDP	-0.0292	-0.0341	-0.0455
	(-0.619)	(-0.724)	(-0.966)
Upgrade	0.0109	0.0009	-0.0080
	(0.087)	(0.008)	(-0.064)
HHI		-0.0167	
		(-0.649)	
HHI_GB		-0.1145**	
		(-2.369)	
HJGZ			-0.0241**
			(-2.250)
HJGZ_GB			-0.0563**
			(-2.192)
_cons	3.3336***	3.4131***	3.5822***
	(5.379)	(5.504)	(5.774)
FE	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	31133	31088	31003
R^2	0.8535	0.8537	0.8538

9. Research Conclusions and Policy Implications

9.1. Research Conclusions

Based on 2010-2023 data of Shanghai and Shenzhen A-share listed companies, this paper uses a difference-in-differences model to evaluate green bonds' impact on corporate carbon emissions. The results show that green bond issuance significantly suppresses corporate carbon emissions, with robust conclusions, demonstrating green finance's role in promoting corporate low-carbon transformation. Mechanism analysis indicates green bonds reduce carbon emission intensity by alleviating financing constraints, strengthening green investment, enhancing executives' green awareness, and improving green innovation. Heterogeneity analysis based on the TOE framework shows the emission reduction effect is more significant in companies with better digital transformation, sufficient high-tech talents, stronger risk-bearing capacity and better ESG performance, as well as in regions with higher industry competition and stricter environmental regulations. The paper reveals green bonds' intrinsic emission reduction mechanism, providing empirical evidence and policy implications for green finance to promote real economy's low-carbon transformation.

9.2. Policy Recommendations

Based on the research findings, the following policy recommendations are proposed:

First, improve the green bond issuance and incentive system and expand policy coverage: simplify the approval process for green bond issuance by low-carbon oriented enterprises, set up differentiated interest rate preferences and fiscal subsidies, encourage multi-industry participation in financing, and strengthen its constraining and restraining effect on corporate carbon emissions. By lowering the institutional financing threshold for green bonds, the financing constraints faced by enterprises in the early stages of green transformation can be effectively alleviated, enabling more enterprises to have the practical conditions to carry out green investment and emission reduction actions, thereby enhancing the policy's transmission effect at the enterprise level.

Secondly, it is crucial to streamline the transmission channels of green bond financing and strengthen its impact: This includes issuing supporting policies to guide green bond proceeds towards green investments such as low-carbon technology upgrades, and establishing a low-carbon benefit assessment mechanism for fund utilization to ensure that funds are translated into concrete corporate carbon reduction actions. Simultaneously, a comprehensive information disclosure and auditing mechanism should be established to enhance the transparency of fund utilization, prevent "greenwashing" and "green-leveraging" practices, and ensure that green bonds truly flow to green assets. By improving the efficiency of fund conversion, the transmission role of green investment in the emission reduction mechanism can be strengthened, resulting in substantial low-carbon output.

Furthermore , a differentiated green bond support strategy will be implemented to precisely stimulate emission reduction efforts: enterprises that excel in areas such as digitalization and the proportion of technical personnel will receive policy support in terms of issuance scale and maturity; enterprises with lower capabilities will be encouraged to address their shortcomings in digitalization, talent, and ESG development, thereby cultivating their basic emission reduction capabilities. By matching the level of green bond support with the technological capabilities of enterprises, the absorption and conversion efficiency of green funds can be improved, enabling enterprises with a strong technological foundation to release emission reduction effects first, while simultaneously driving weaker enterprises to gradually improve their green transformation capabilities.

Furthermore , optimizing the coordination of regional industrial and environmental policies can amplify the emission reduction effect: In highly competitive and heavily regulated regions, green bonds should be linked to local industries and environmental policies and tied to resources such as carbon quotas; policy services should be extended to regions with weak regulations and insufficient competition, the regulatory system should be improved, and the balanced release of regional emission

reduction effects should be promoted. Moreover, differentiated green bond usage guidelines should be formulated based on regional differences in environmental regulatory intensity and industrial structure, deeply integrating bonds with regional industrial upgrading paths, enhancing the synergy of local government policies, and increasing the marginal carbon emission reduction effect of green financial instruments at the regional level.

Finally, cultivate enterprises' intrinsic motivation for green development and solidify the foundation for carbon emission reduction: enhance corporate executives' green awareness through policy guidance and training, establish a green innovation assessment and incentive mechanism, and give priority support to enterprises with significant innovation achievements in issuing bonds, forming a virtuous cycle of "green bonds - green innovation - carbon emission reduction". As executives' green awareness improves, enterprises are more likely to incorporate low-carbon goals into their long-term development strategies, promote the continuous implementation of green innovation and emission reduction behaviors at the decision-making level, and enhance the long-term emission reduction effect of green bond policies.

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