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Green Bonds and Corporate Innovation Efficiency

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Abstract. The impact of green bonds on corporate innovation efficiency is a significant practical issue. This study utilizes data from listed companies between 2007 and 2024 to examine the effects of green bond issuance on corporate innovation efficiency. Findings reveal that green bond issuance exerts a significant positive influence on corporate innovation efficiency, a conclusion that remains robust after undergoing a series of stability tests. Heterogeneity analysis indicates that the effect is more pronounced among non-state-owned enterprises, heavily polluting industries, eastern regions, and large-scale enterprises. Mechanism analysis indicates that green bonds enhance corporate innovation efficiency by alleviating financing constraints, improving environmental disclosure quality, and elevating executives' green awareness. These findings align with the logic that green bonds provide stable, targeted funding for corporate innovation activities, thereby stimulating their innovative vitality. This conclusion holds significant implications for guiding green finance to empower corporate technological innovation and enhance new-quality productive forces.

Keywords: Green Bonds, Innovation Efficiency; Financing Constraints; Environmental Disclosure; Green Awareness Among Executives.

1. Introduction

China's economy has shifted from a phase of high-speed growth to one of high-quality development, where green transformation and innovation-driven growth are paramount to sustainable economic expansion. In September 2020, the goals of achieving carbon peak by 2030 and carbon neutrality by 2060 were first explicitly proposed. Against this backdrop, China's green bond market has experienced rapid growth. According to the China Sustainable Debt Market Report, by the end of 2024, China's cumulative green bond issuance reached 3.2 trillion yuan, ranking third globally in 2024 issuance volume. Therefore, scientifically evaluating the effectiveness of green bonds holds significant practical importance to ensure green finance effectively serves the innovative development of the real economy, continuously empowers economic transformation, and contributes to achieving the “dual carbon” goals.

Academic research has examined the impact of green bonds on corporate market communication and investment-financing behavior from multiple perspectives. Flammer found that issuers demonstrated improved environmental performance following green bond issuance [1]. Baulkaran observed that corporate green bond issuance elicits a significantly positive stock price reaction [2]. Zhang, X. Q., & Wang, Z.W. demonstrated that the green attributes of green bonds can substantially reduce corporate financing costs, with enhanced environmental performance and innovation capabilities further amplifying the signaling effect of green bonds in lowering financing costs [3]. Building upon prior literature, this study aims to further explore the impact of green bond issuance on corporate innovation efficiency.

Theoretically, issuing green bonds promotes corporate innovation efficiency. Due to information asymmetry, investors' risk aversion can hinder corporate financing, whereas the high-quality disclosure required by green bonds helps companies attract more green innovation investment [4]. Green bonds feature stricter and more targeted issuance regulations compared to conventional bonds. Regarding information disclosure, they mandate continuous public reporting on fund utilization, project progress, and environmental benefits [5]. Li J. P., & Cao X. T. found that synergistic effects

between executives' green cognition and media attention can enhance information disclosure quality [6]. Green bond issuance alleviates information asymmetry between companies and investors, eases financing constraints, and promotes corporate innovation.

However, green bonds may also exert a dampening effect on innovation efficiency, stemming from the high compliance costs and restrictions on fund usage imposed by their stringent regulations[1]. Some firms resort to improper means to circumvent these drawbacks. Ma, L. Y. & Wang, S. C. found that companies often exploit regulatory loopholes to engage in opportunistic "greenwashing" behavior [7]. Consequently, the stringent regulations governing green bonds impose high issuance costs and low capital flexibility on enterprises, exacerbating funding difficulties and even fostering greenwashing practices, thereby suppressing corporate innovation.

The above analysis indicates that the theoretical direction of green bonds' impact on corporate innovation efficiency remains uncertain and requires empirical verification. Using a sample of Chinese A-share listed companies from 2007 to 2024, this study demonstrates that issuing green bonds positively influences corporate innovation efficiency. This result remains robust after employing parallel trend tests, placebo tests, PSM-DID, alternative measures for the dependent variable, and exclusion of anomalous years. Further research reveals that this effect is more pronounced in eastern regions and among state-owned enterprises. Mechanism tests indicate that green bonds enhance corporate innovation efficiency primarily by alleviating financing constraints, improving the quality of environmental information disclosure, and elevating executives' green awareness. These conclusions align with the logic that green bonds alleviate financial pressures and promote innovation.

The contributions of this paper may include: First, it expands research on the economic effects of green bond issuance. Existing studies on green bonds have largely focused on financial market dimensions, such as their impact on corporate financing costs [3] and stock prices [2]. Building upon this foundation, this paper extends the economic implications to the operational level of corporate activities, examining the impact of green bonds on corporate innovation efficiency. Second, it supplements research on the factors influencing corporate innovation. Existing literature on corporate innovation drivers primarily adopts traditional perspectives such as corporate governance [8], equity structure [9], and financing constraints [10]. This paper explores the topic from the perspective of green bonds as an emerging external financing tool, focusing on innovation efficiency rather than simple R&D inputs or outputs, thereby providing a new dimension for understanding corporate innovation activities. Third, it holds practical significance. The findings offer regulatory authorities a reference for evaluating the effectiveness of green bonds and optimizing related systems, while also providing direction for enterprises on how to leverage green financial instruments to achieve their own innovation and development.

The structure of this paper is as follows: Part II presents the literature review, Part III outlines the research hypotheses and empirical design, Part IV reports the empirical findings and analysis, Part V offers further analysis, and Part VI concludes the study.

2. Literature Review

2.1. Research on Green Bonds

Green bonds are debt instruments that raise funds specifically for supporting green projects [11]. The core distinction from conventional bonds lies in their "green" attributes, specifically manifested through specific requirements regarding fund usage, project evaluation, management, and information disclosure [12]. The China Green Bond Principles (hereinafter referred to as the "Principles"), issued in July 2022, require 100% of raised funds to be invested in green projects. The November 2020 Application Guidelines No. 2 for Reviewing Corporate Bond Issuance and Listing mandates that at least 70% of raised funds must be invested in designated green sectors [13]. Regarding project assessment, domestic green bond issuers generally commission independent

certification agencies to conduct evaluations and issue reports. The People's Bank of China's documents also support the adoption of professional certification mechanisms for green financial bonds [14]. Regarding raised funds management, the “Principles” require issuers to establish either a dedicated raised funds supervision account or a specialized ledger to ensure funds are strictly used for designated purposes, maintaining full traceability throughout the process [15]. Changes in the use of raised funds must be restricted to green projects. Regarding information disclosure, the “Principles” stipulate that green bond issuers should regularly report details on fund utilization, project progress, and environmental benefits.

The unique “green” attributes of green bonds make them a crucial tool for corporate market communication and image management. Baulkaran found that announcements of green bond issuances by companies can trigger significantly positive stock price reactions, but excessively high coupon rates may provoke negative investor responses [2]. Chai, H. R. et al. noted that despite lower interest rates, green bonds outperform conventional bonds in terms of capital gains and liquidity, partially offsetting the negative impact of reduced interest income and still effectively attracting investors [16]. Flammer employed a difference-in-differences approach to demonstrate that the environmental commitment signals conveyed by green bonds also help companies attract more socially responsible long-term investors, particularly for first-time issuers and those with authoritative certification [1]. Liu, S. Q. et al. also observed that under the “carbon neutrality” objective, institutional investors exhibit pronounced green preferences [17]. Their shareholding ratio not only increases significantly after the company issues green bonds but also rises further as the bonds become more “green”. Not all market participants in the green bond sector are driven by environmental incentives. Some companies issue green bonds opportunistically, engaging in strategic “greenwashing” behavior. Ma, L. Y., & Wang, S. C. attribute the causes of greenwashing to two factors: external causes stemming from information asymmetry, inconsistent market standards, regulatory pressures, and societal expectations; and internal causes driven by corporate profit-seeking, where firms leverage the convenience of green bonds to pursue purely economic gains [7]. Research by Du X. based on the Chinese market indicates that consumers can effectively distinguish between corporate greenwashing and genuine environmental performance, and media exposure of greenwashing significantly impacts corporate stock prices and generates negative spillover effects on other companies in the same industry with poor environmental records [18].

The issuance of green bonds by enterprises carries a series of far-reaching practical economic consequences. The environmental attributes of green bonds increase media and investor scrutiny of issuing companies [19]. This external oversight from stakeholders, combined with the high disclosure requirements inherent to green bonds, can effectively curb opportunistic behavior by corporate management [20]. Consequently, green bonds serve as an effective external governance mechanism to enhance internal corporate governance. Sassen et al. found that ESG dimensions exert differential effects on corporate risk, with improved ESG performance reducing both overall and specific risks [21]. Among these, social dimension performance emerged as the most critical factor in mitigating risk. Thus, green bond issuance can lower corporate risk by enhancing ESG performance. Dong, K. Y. et al. conducted empirical research using prefecture-level city data in China, revealing that green bond issuance significantly promotes regional carbon emission reductions, with this effect being more pronounced in areas with stricter environmental regulations [22]. Yang, J. Y. & Mei, X. Y. analyzed panel data from A-share listed companies between 2014 and 2022, finding that corporate ESG performance significantly improved after green bond issuance, with this effect exhibiting dynamic persistence [23]. Beyond positive impacts, green bond issuance carries the drawback of high costs. The 2015 OECD report notes that meeting green bond requirements entails relatively high expenses [24]. In some markets, obtaining professional certification body can cost as much as $100,000, posing a significant barrier for smaller issuers. Subsequent project tracking report requirements further drive-up costs.

2.2. Literature Review on Corporate Innovation

According to Holmstrom and Ju, X. S. et al., innovation activities exhibit inherent characteristics such as high risk, high cost, unpredictability, long-term nature, and uniqueness [25, 26]. These traits, particularly high risk and long-term orientation, lead to severe information asymmetry between financiers and investors. Since innovators invariably possess greater insight into a project's true circumstances than investors, the latter's difficulty in discerning project quality necessitates demanding higher risk premiums. This significantly elevates the financing costs and challenges associated with corporate innovation activities [27]. Compounded by the requirement for comprehensive, long-term resource commitments—spanning equipment to human capital—and the slow realization of returns, these factors further intensify enterprises' financial pressures [25]. In summary, the complexity of innovation and the high cost of financing necessitate that enterprises have a critical need for stable funding and tolerance for failure.

Given the high dependence of innovation activities on capital, stable and ample financing is a prerequisite for enhancing innovation efficiency. First, as a traditional external financing channel, bank credit plays an indispensable role in corporate innovation. Kortum & Lerner found that venture capital has a significant positive impact on innovation: After controlling for the influence of traditional corporate R&D expenditures, increased venture capital investment was strongly correlated with higher patent output rates. Conservative estimates suggest its innovation-stimulating effect is approximately three times that of traditional R&D [28]. Ren, C. found in a study of technology enterprises that bank credit significantly promotes technological innovation, with this effect being particularly pronounced in non-state-owned enterprises [29]. Second, venture capital possesses unique advantages due to the high risk associated with innovation projects. Guo, X. D. confirms that government subsidies can significantly boost corporate innovation and R&D, enhancing output, while financing constraints not only stifle innovation but also diminish the effectiveness of positive policies such as government grants [30].

Beyond financial backing, an environment that tolerates failure is equally vital for boosting innovation efficiency. Graham et al. concluded through a survey of 401 financial executives and 20 in-depth interviews that executives are willing to sacrifice genuine economic value to achieve short-term profit targets: 55% abandoned potential projects to meet quarterly earnings expectations, while 80% cut expenditures such as R&D spending [31]. The intense short-term performance pressure stemming from the market's severe negative reaction to missed profit targets causes executives to sacrifice numerous innovation opportunities. In contrast, institutional investors can protect and insulate managers through effective oversight, preventing their dismissal due to short-term profit fluctuations [9]. Galasso & Simcoe found that the appointment of an overconfident CEO correlates positively with both R&D investment and output, potentially even steering the company toward new technological directions [32]. Creating an environment tolerant of failure requires institutional designs that explicitly embrace failure. Manso proposed that since innovation is inherently a high-risk endeavor, the punitive mechanisms of traditional performance evaluations tend to stifle it, and ideal incentives should tolerate and even reward early failures while guaranteeing rewards for ultimate success [8]. Research data from Aghion et al. indicates that when institutional ownership is high, CEOs face reduced likelihood of dismissal due to declining profitability [9]. This increases their willingness to take risks on innovation activities, thereby stimulating corporate innovation.

Some literature has begun exploring the impact of green bonds on corporate innovation. Shen, Y. et al. confirmed that green bond issuance significantly enhances corporate green innovation, manifested as increased green patents [33]. The primary impact mechanisms include: first, “financing constraint relief”, such as the “resource effect” proposed by Wang, Y., & Feng, J. H. [34], which provides long-term stable funding for green R&D; second, “signaling” and “governance optimization”, as Li et al. noted that it signals environmental commitments and improves information disclosure [35]; and third, the “monitoring effect” discovered by Wang, Y., & Feng, J. H. which promotes innovation by reducing agency costs [34].

In summary, on the one hand, green bonds leverage their "green" attributes to trigger signaling games and economic effects, serving as corporate communication and branding tools. On the other hand, corporate innovation characterized by high risk and long cycles, relies significantly on stable financing and a forgiving environment to enhance efficiency. While existing research confirms that green bonds promote corporate innovation, most studies are limited to the dimensions of green output and innovation input, neglecting efficiency mechanisms. This paper explores the impact of green bonds on innovation efficiency through dual pathways of financing constraints and governance effects, providing theoretical support for enhancing corporate innovation effectiveness through green finance.

3. Research Hypothesis

From an external perspective, issuing green bonds can significantly alleviate financing constraints and boost corporate innovation efficiency. Financing constraints are a key factor limiting technological innovation, given that innovation requires substantial long-term investment and carries high risks. As a specialized financing tool, green bonds broaden corporate financing channels. On one hand, the long-term, stable, targeted funding from green bonds reduces enterprises' reliance on high-cost short-term external capital, mitigating the negative impact of financial pressure on innovation [4]. On the other hand, green bonds serve as a supplement and alternative to bank loans, thereby optimizing corporate financing structures and reducing financial burdens to some extent [36]. Furthermore, the "green" attributes of green bonds demonstrate corporate social responsibility, potentially attracting investors with such preferences. This broadens the financing base and diversifies funding sources [37]. With financing constraints alleviated, the enterprise could increase R&D investment, explore new technological pathways, thereby producing high-quality innovative outcomes and improving innovation efficiency. Based on this, the following hypothesis is proposed:

H1: Green bonds enhance corporate innovation efficiency by alleviating financing constraints.

The issuance mechanism of green bonds helps improve the quality of environmental information disclosure and boost corporate innovation efficiency. Information asymmetry between investors and enterprises makes it difficult for investors to accurately assess the true value and risks of corporate innovation projects, thereby increasing financing difficulties for enterprises [4]. Compared to conventional bonds, green bonds feature targeted regulations regarding fund usage, capital management, project evaluation, and selection. They impose stricter disclosure requirements on information such as fund utilization, project progress, and environmental benefits [5]. High-quality environmental disclosure by enterprises also serves as an effective commitment to green development, positively enhancing market trust and social recognition, thereby effectively attracting innovative capital [38]. Additionally, it promotes knowledge sharing within the industry and optimizes corporate innovation technologies and strategies [4]. In summary, green bonds compel enterprises to disclose high-quality environmental information, thereby expanding R&D investment and enhancing innovation quality through capital attraction and knowledge sharing, ultimately boosting innovation efficiency. Based on this, the following hypothesis is proposed:

H2: Green bonds enhance corporate innovation efficiency by improving the quality of environmental information disclosure.

Internally, the process of issuing green bonds deepens corporate executives' understanding of green concepts, thereby enhancing innovation efficiency. As a targeted financing tool, green bonds inherently guide executive strategy and corporate development direction. During issuance, executives must clarify the specific requirements of green bonds, gradually deepen their grasp of green principles, and increase focus on environmental issues and green development strategies—thus enriching their green awareness [37]. According to advanced theories, executives' green cognition reflects their attitudes, values, and experiences—including perceptions of green competitive advantages, social responsibility awareness, and external pressure—significantly influencing corporate innovation model choices [39, 40]. Executives with higher green cognition are more likely to view innovation as

critical to long-term corporate development. Vanke's executives have demonstrated strategic-level support and guidance for the company's green technology R&D and application. Thus, executive green cognition serves as a crucial intermediary link connecting green bond funding with internal corporate innovation vitality. Based on this, the following hypothesis is proposed:

H3: Green bonds enhance corporate innovation efficiency by elevating executives' awareness of environmental sustainability.

4. Empirical Design

To examine whether green bonds can enhance corporate innovation efficiency, this paper adopts the regression model established by Zhao, L. L. et al. and Zhao, H. H., & Pan, L. J., as follows [41, 42]:

$$Eff_{it} = \beta_0 + \beta_1 Treat_i \times Post_t + \beta_2 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (1)$$

Among these, Eff represents corporate innovation efficiency. Existing literature primarily measures innovation activities based on innovation outputs or inputs. Drawing on the methodology of Liu et al. [43], this study calculates corporate innovation efficiency using the ratio of innovation outputs to R&D investment. Specifically, patent volume serves as a proxy variable for corporate innovation outputs, while the explained variable—corporate innovation efficiency (Eff)—is defined as the ratio of patent volume to R&D investment. The core explanatory variable $Treat_i \times Post_t$ is a dummy variable indicating whether firm i issued green bonds in year t. It is coded as 1 if firm i issued green bonds in year t and 0 otherwise. This study focuses on the estimated value of regression coefficient β_1. A significantly positive estimate of β_1 indicates that issuing green bonds enhances corporate innovation efficiency, thereby validating the study's hypothesis.

Table 1. Detailed Definitions of Key Variables

Variable Type	Variable Symbol	Variable Name	Variable Declaration
Dependent Variable	Eff	Corporate Innovation Efficiency	Number of Patents / R&D Investment
Independent variable	Treat×Post	Green Bond Issuance	Green Bond Issuer Grouping and Time Grouping Cross-Product
Control variables	Assets	Enterprise Total Assets	Listed company data
	Liabs	Enterprise Total Liabilities	Listed company data
	ROE	Return on Equity	Net profit / Net Assets
	INV	Inventory ratio	Inventory value / Total Assets
	CashFlow	Cash flow	Net Cash Flow from Operating Activities
	Board	Board membership	Board membership
	Indep	Proportion of Independent Directors	Independent Directors / Board membership
	top5	Top 5 Shareholders' Shareholding Ratios	Combined shareholding ratio of the top five shareholders
	ListAge	Age of Enterprise Listing	Difference between the estimated year and the listing year

$Control_{it}$ represents a series of control variables, including: Total Assets *(Assets)*, Total Liabilities *(Liabs)*, Return on Equity *(ROE)*, Inventory Ratio *(INV)*, Cash Flow *(CashFlow)*, Number of Board

Members *(Board)*, Proportion of Independent Directors *(Indep)*, Top Five Shareholders' Holding Ratio *(top5)*, Age of Listing *(ListAge)*. μ_i and λ_t denote individual fixed effects and year fixed effects, respectively, while ε_{it} represents the residual term. Furthermore, to address potential cross-sectional autocorrelation issues, robust standard errors clustered at the industry level were applied to all models. Detailed definitions of key variables are provided in Table 1.

4.1. Data Source

This study utilizes data from Chinese A-share listed companies (CSMAR) spanning 2007 to 2024. After screening and excluding ST and *ST stocks, financial sector firms, and samples with missing values, a final dataset of 47,556 observations was retained. All variables underwent 1% right-tail trimming.

5. Descriptive statistics

Table 2. Descriptive Statistics of Key Variables

	(1)	(2)	(3)	(4)	(5)
VARIABLES	N	mean	sd	min	max
Eff	47,556	1.169	1.290	0	8.096
TreatPost	47,556	0.0932	0.291	0	1
INV	47,556	0.468	7.670	0	1,436
Board	47,556	8.530	1.716	0	18
Indep	47,556	3.153	0.586	0	8
Assets	47,556	1.606e+10	8.394e+10	0	2.903e+12
Liabs	47,556	9.487e+09	5.375e+10	-2.033e+06	2.172e+12
top5	47,556	53.54	15.72	0.811	99.23
ListAge	47,556	9.849	7.777	0	33
CashFlow	47,556	-1.664e+09	1.584e+10	-1.049e+12	5.634e+11
ROE	47,556	0.0465	4.119	-207.4	713.2

Table 2 presents the descriptive statistics for the key variables in this study. The mean value of the dependent variable, corporate innovation efficiency (*Eff*), is 1.169 with a standard deviation of 1.290. A significant gap exists between the maximum and minimum values, indicating substantial variation in innovation efficiency levels among the sample firms. The key explanatory variable ($Treat_i \times Post_t$) has a mean of 0.0932 and a standard deviation of 0.291, indicating that approximately 9.32% of observations in the sample belong to the treatment group that issued green bonds. Regarding other control variables: Average total assets *(Assets)* reached approximately ¥16.06 billion; Average number of board members *(Board)* was 8.530; Average proportion of independent directors *(Indep)* was 3.153; Average return on equity *(ROE)* was 4.65%.

6. Analysis of Benchmark Regression Results

This paper employs a stepwise regression approach, with Table 3 presenting the benchmark regression analysis. Specifically, Column (1) presents the simple regression of *Eff* on $Treat_i \times Post_t$ without any control variables or fixed effects; Column (2) adds year-specific and industry-specific fixed effects to Column (1) to control for macroeconomic variations and industry-specific characteristics; Column (3) further incorporates firm-level control variables; and Column (4) includes all control variables alongside dual fixed effects for both year and industry.

Table 3. Benchmark Regression Analysis

VARIABLES	(1) Eff	(2) Eff	(3) Eff	(4) Eff
TreatPost	0.461***	0.097**	0.456***	0.122***
	(11.271)	(2.231)	(11.314)	(3.027)
Assets			0.000**	0.000***
			(2.368)	(2.989)
Liabs			-0.000	-0.000
			(-1.231)	(-1.594)
ROE			-0.000	0.000
			(-0.004)	(0.205)
INV			-0.004	-0.000
			(-1.503)	(-0.653)
CashFlow			-0.000***	-0.000***
			(-2.963)	(-3.112)
Board			-0.033**	0.029**
			(-2.464)	(2.504)
Indep			0.170***	0.164***
			(4.186)	(5.008)
top5			-0.003***	0.002*
			(-2.909)	(1.810)
ListAge			0.002	0.022***
			(1.004)	(9.332)
Constant	1.126***	-0.324***	0.966***	-1.406***
	(64.617)	(-4.330)	(8.613)	(-10.306)
Observations	47,556	47,556	47,556	47,556
R-squared	0.011	0.224	0.074	0.311
Firm FE	NO	YES	NO	YES
Year FE	NO	YES	NO	YES

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent t-values. The same applies below.

The regression results indicate that the coefficient of the core explanatory variable $Treat_i \times Post_t$ is significantly positive across all four model specifications, suggesting that issuing green bonds positively promotes corporate innovation efficiency. Specifically, in the model accounting for all control variables along with dual fixed effects for industry and year, the regression coefficient for $Treat_i \times Post_t$ was 0.122, significant at the 1% level. This finding indicates that even after controlling for other confounding factors, green bond issuance still significantly enhances corporate innovation efficiency. In summary, these benchmark regression results validate the hypotheses proposed in this study.

7. Robustness Test

7.1. PSM-DID

To mitigate sample selection bias and ensure the robustness of the benchmark regression results, this study employs a combination of propensity score matching and a double difference approach for robustness testing. Specifically, using control variables as covariates, a 1:1 nearest neighbor matching is performed on the samples. The DID regression results for the matched samples are presented in Table 4 Column (1) controls for all covariates along with industry and year fixed effects. The coefficient for the core interaction term $Treat_i \times Post_t$ is 0.145, significantly positive at the 1% level.

This result indicates that after mitigating sample selection bias, green bonds still significantly enhance corporate innovation efficiency, confirming the robustness of the paper's core findings.

Table 4. Robustness Test

VARIABLES	(1) Eff	(2) IOE	(3) Eff
TreatPost	0.145***	0.009***	0.107**
	(2.828)	(2.634)	(2.461)
Assets	0.000**	0.000	0.000***
	(2.527)	(0.265)	(2.802)
Liabs	-0.000**	0.000	-0.000*
	(-2.060)	(0.198)	(-1.717)
ROE	-0.002	-0.000	0.000
	(-0.540)	(-1.318)	(0.137)
INV	-0.026*	0.000	-0.000
	(-1.888)	(1.355)	(-0.543)
CashFlow	-0.000***	0.000	-0.000***
	(-4.453)	(1.013)	(-4.420)
Board	0.029	0.000	0.029**
	(1.475)	(0.657)	(2.385)
Indep	0.243***	0.000	0.163***
	(4.385)	(0.056)	(4.629)
top5	0.002	0.000	0.003**
	(1.148)	(0.890)	(2.551)
ListAge	0.027***	0.000	0.019***
	(6.259)	(0.090)	(7.572)
Constant	-1.125***	0.228***	-1.427***
	(-3.785)	(25.077)	(-9.754)
Observations	6,962	38,104	34,695
R-squared	0.294	0.621	0.323
Firm FE	YES	YES	YES
Year FE	YES	YES	YES

7.2. Change the measurement method for the dependent variable

To ensure that the conclusions are not biased by the measurement of the dependent variable (firm innovation efficiency), this study replaces *Eff* with *IOE* as an alternative indicator for the core dependent variable. The regression results are shown in Column (2) in Table 4. The coefficient for the treatment group is 0.009 and is positively significant at the 1% level, consistent with the benchmark regression results.

7.3. Exclude anomalous years

To eliminate the interference of macroeconomic shocks from the 2008 global financial crisis and the 2015 abnormal fluctuations in China's stock market on the findings of this study, we excluded observations from 2008 and 2015 from the sample and reran the benchmark regression. As shown in Table 4, the coefficient of the core explanatory variable in Column (3) is 0.107, which is positively significant at the 5% level. This confirms the robustness of our core conclusion.

7.4. Parallel Trend Test

To test whether the difference-in-differences model in this paper satisfies the parallel trends assumption—that is, whether firms issuing green bonds and those not issuing green bonds exhibited identical development trends prior to the policy—this study constructed a research model covering

the five periods preceding and the five periods following the policy implementation, using the period immediately preceding the green bond issuance (before1) as the baseline group. The regression results are shown in Fig. 1. Prior to the policy implementation, the coefficients of all dummy variables are statistically insignificant. This indicates that before issuing green bonds, there was no significant difference in innovation efficiency between the treatment group and the control group, satisfying the parallel trends assumption.

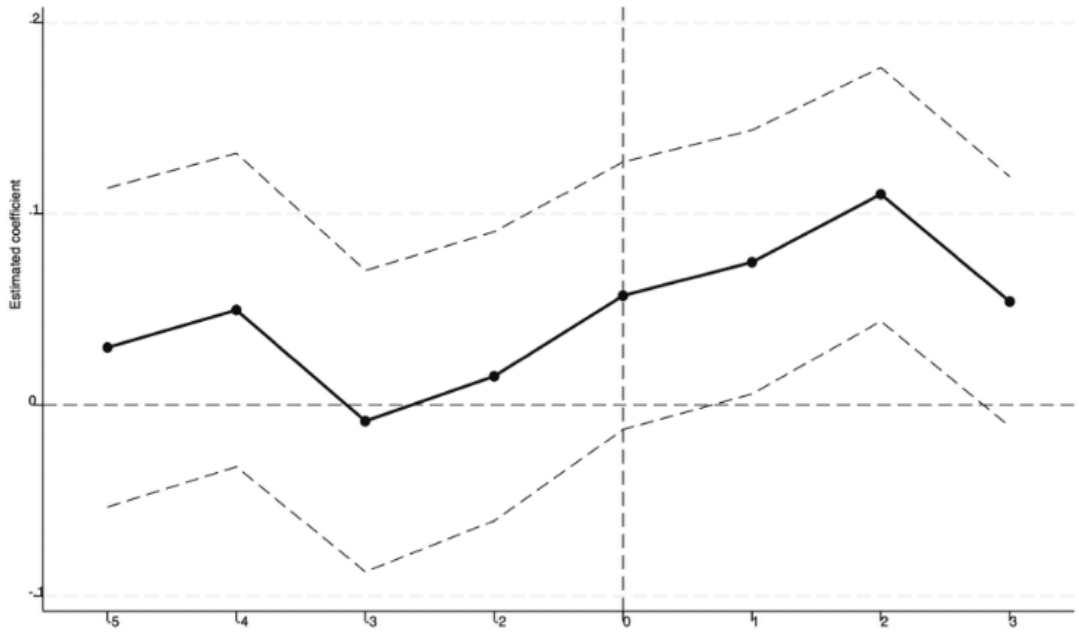

Figure 1. Parallel Trend Test

7.5. Placebo Test

To further rule out the influence of random disturbances or other unobserved factors on the benchmark regression results, a placebo test was conducted in this study. Specifically, the value of the core interaction term $Treat_i \times Post_t$ was randomly permuted within the sample, and the benchmark regression was performed 500 times. The results, shown in Fig. 2, reveal that the distribution of the 500 "pseudo-coefficients" is highly concentrated around zero, while the actual estimated coefficient of 0.122 lies distinctly at the extreme end of this distribution. This strongly indicates that the core findings of this paper pass the placebo test, demonstrating robust validity.

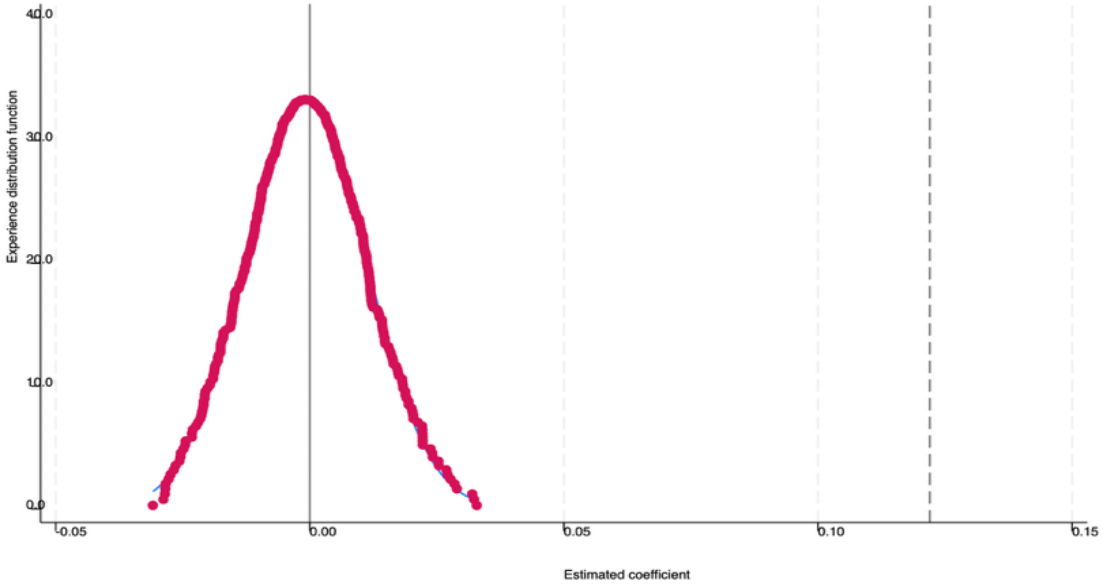

Figure 2. Placebo Test

8. Heterogeneity Analysis

Table 5. Heterogeneity Analysis Results

VARIABLES	(1) SOE	(2) Non-SOE	(3) Heavy Pollution	(4) Non-Heavy Pollution	(5) Eastern Part	(6) Central,Western Part	(7) Small Firms	(8) Large Firms
TreatPost	0.073	0.113**	0.152**	0.098*	0.108**	0.105	0.061	0.140**
	(0.915)	(2.433)	(2.042)	(1.922)	(2.105)	(1.363)	(1.480)	(2.335)
Assets	0.000***	0.000***	-0.000	0.000***	0.000***	0.000***	0.000***	0.000***
	(2.624)	(7.784)	(-0.219)	(7.497)	(2.882)	(2.672)	(15.384)	(3.029)
Liabs	-0.000	-0.000***	0.000***	-0.000***	-0.000*	0.000	-0.000***	-0.000*
	(-0.818)	(-7.207)	(3.528)	(-6.609)	(-1.748)	(0.342)	(-4.983)	(-1.717)
ROE	0.015	0.002	0.034***	0.004	0.007	0.017***	0.001	0.001
	(0.865)	(0.694)	(2.588)	(1.109)	(1.388)	(2.851)	(1.170)	(0.198)
INV	0.000	-0.008	-0.117***	0.000	-0.000	0.001***	-0.000	-0.005**
	(0.555)	(-0.806)	(-2.595)	(0.084)	(-0.468)	(2.896)	(-0.045)	(-2.261)
CashFlow	-0.000	-0.000	-0.000*	-0.000*	-0.000***	0.000	0.000	-0.000***
	(-1.477)	(-1.051)	(-1.704)	(-1.852)	(-2.797)	(0.083)	(0.499)	(-3.178)
Board	-0.013	0.041***	0.014	0.037**	0.024	0.036*	0.022**	-0.003
	(-0.680)	(2.883)	(0.696)	(2.471)	(1.528)	(1.927)	(2.176)	(-0.169)
Indep	0.224***	0.029	0.089	0.161***	0.170***	0.080	-0.035	0.203***
	(4.496)	(0.676)	(1.539)	(3.752)	(3.769)	(1.535)	(-1.148)	(4.355)
top5	0.007***	-0.003**	0.005***	-0.000	0.003**	-0.001	-0.005***	0.005***
	(4.147)	(-2.401)	(2.846)	(-0.035)	(1.995)	(-0.882)	(-5.466)	(3.883)
ListAge	0.011***	0.007**	0.010***	0.023***	0.027***	0.004	-0.015***	0.015***
	(2.766)	(2.108)	(2.678)	(7.515)	(8.185)	(1.070)	(-6.814)	(4.839)
Constant	-1.562***	-0.541**	-1.211***	-1.427***	-1.114***	-1.078***	-0.159	-1.505***
	(-8.760)	(-2.471)	(-5.808)	(-8.225)	(-4.904)	(-5.972)	(-1.127)	(-7.004)
Observations	14,207	21,828	10,880	25,155	25,511	10,524	17,237	17,458
R-squared	0.471	0.291	0.267	0.378	0.331	0.381	0.267	0.428
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES

8.1. Type of enterprise

State-owned enterprises are state-controlled and serve strategic objectives of the country, while non-state-owned enterprises pursue commercial profits through market-oriented approaches. Li, B. Y. et al. found that the significant financing advantages of state-owned enterprises limit the effectiveness of their green bonds in enhancing innovation efficiency [44]. Furthermore, agency problems weaken the incentive for innovation. Zhao, L. L. et al. argue that state-owned enterprises (SOEs) bear multiple strategic objectives and social responsibilities, with resource dispersion impairing innovation efficiency [42]. If green bond financing constraints on SOEs are only partially alleviated and their innovation incentives remain weak, this study anticipates that green bonds will exert a more pronounced impact on the innovation efficiency of non-state-owned enterprises.

This study follows the methodology of Zhao, L. L. et al. [42], classifying samples into state-owned and non-state-owned enterprises based on ownership characteristics and identifying SOEs using an instrumental variable. The regression analysis in Table 5 indicates that the coefficient for the explanatory variable in non-state-owned enterprises is 0.113, which is significantly positive, while the coefficient in state-owned enterprises is 0.073 and not statistically significant. This result supports the inference that green bonds enhance the innovation efficiency of non-state-owned enterprises.

8.2. Whether heavy pollution

As major pollution emitters, heavily polluting enterprises are more inclined toward green bond financing due to their environmental responsibilities. Ge, C. R., & Han J. emphasize that such enterprises face stringent environmental regulations and high financing barriers [45]. Wang Q. et al. found they urgently require financial support for green transformation [46]. If green bonds can alleviate financing constraints and promote innovation, this paper anticipates their effects should be more pronounced among heavily polluting enterprises.

Following the methodology of Zhang, Z. B., & Zhang, R. X. [4], this study categorizes sample enterprises into heavily polluting industries and non-heavily polluting industries based on the "Guidelines for Environmental Information Disclosure of Listed Companies (2010)". Column (3) in Table 5 shows an explanatory variable coefficient of 0.152 ($p<0.05$) for the heavily polluting group, while Column (4) shows a coefficient of 0.098 ($p<0.1$) for the non-polluting group. This indicates that green bond financing has a more pronounced promotional effect on the innovation efficiency of heavily polluting enterprises, thereby validating the research hypothesis.

8.3. Corporate Region

Eastern regions possess well-developed market mechanisms that better leverage various resources, resulting in more pronounced green bond issuance outcomes in these areas. Zhang, Y. found that the eastern region possesses developed financial markets and low-cost green bonds [47]. Yang, J. Y., & Mei, X. Y. emphasized that this area boasts superior infrastructure, abundant technical talent, a strong foundation for innovation, and high financing efficiency [23]. Therefore, this paper anticipates that the innovation effect of green bonds will be more pronounced in the eastern region due to its outstanding external conditions.

This study adopts the regional classification framework of the CNBS and draws upon the research by Yang, J. Y., & Mei, X. Y. [23], to divide the country into eastern and central and western regions for regression analysis. Table 5 indicates that the coefficient for the explanatory variable in the eastern region is 0.108 (significant), whereas it is insignificant in the central and western region. This suggests that the promotional effect of green bonds on corporate innovation efficiency exhibits regional variations, with more pronounced effects in economically developed areas.

8.4. Enterprise Scale

Large enterprises leverage their reputational advantages and resource endowments to effectively reduce the financing costs and difficulties associated with green bonds, making their innovative effectiveness more pronounced among large corporations. Li, C. H. confirms that large enterprises issuing green bonds more readily gain market attention and investor recognition [37]. Wang, Q. et al. emphasize that large enterprises possess abundant resources, strong R&D capabilities, and high capital conversion efficiency [46]. Consequently, this paper anticipates more pronounced green bond issuance effects among large enterprises, given their comprehensive competitive advantages.

This study adopts the methodology of Liu, J. K., & Xiao, Y. Y. [48], defining firm size based on the median of the logarithm of total assets. Table 5 shows that the coefficient of the explanatory variable is 0.140 (significantly positive) for large firms and 0.061 (insignificant) for small firms. This suggests that the positive impact of green bonds on innovation is primarily evident in larger enterprises, consistent with the inference.

9. Mechanism Analysis

This paper employs a two-step approach for mechanism testing. The formula is as follows:

$$SA_{it} = \beta_0 + \beta_1 Treat_i \times Post_t + \beta_2 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (2)$$

$$QEID_{it} = \beta_0 + \beta_1 Treat_i \times Post_t + \beta_2 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (3)$$

$$MEA_{it} = \beta_0 + \beta_1 Treat_i \times Post_t + \beta_2 Control_{it} + \mu_i + \lambda_t + \varepsilon_{it} \quad (4)$$

SA Index is employed to assess financing constraints, following the methodology of Yang, J. Y., & Mei, X. Y. [23]. The regression results (Table 6, Column 1) reveal that the interaction term coefficient between the SA Index and financing constraints is negative at the 10% significance level, supporting

the theoretical expectation that green bonds alleviate financing constraints. This finding aligns with the theoretical assumptions of this study.

Table 6. Mechanism Analysis

VARIABLES	(1) SA	(2) QEID	(3) MEA
TreatPost	-0.114*	5.344***	0.735***
	(-1.735)	(4.893)	(3.862)
Assets	0.046	3.860***	0.259***
	(1.465)	(10.814)	(8.554)
Liabs	0.137***	-3.728***	-0.409***
	(2.694)	(-3.392)	(-3.656)
ROE	0.388***	8.744***	0.570***
	(3.075)	(4.309)	(2.596)
INV	-0.331***	-3.840**	0.428***
	(-3.910)	(-2.548)	(2.684)
CashFlow	-0.019	2.164***	0.006
	(-0.736)	(4.262)	(0.116)
Board	0.068	0.043	0.207
	(0.848)	(0.037)	(1.645)
Indep	0.360***	6.065**	0.179
	(2.944)	(2.560)	(0.853)
top5	-0.045	2.618***	-0.198**
	(-0.923)	(2.821)	(-2.210)
ListAge	0.740***	82.961***	0.015
	(3.956)	(42.438)	(0.093)
Constant	-2.211***	-108.317***	-5.023***
	(-3.670)	(-10.759)	(-6.024)
Observations	22,948	26,984	27,014
R-squared	0.007	0.414	0.157
Firm FE	YES	YES	YES
Year FE	YES	YES	YES

QEID represents the quality of environmental information disclosure. Following the methodology of John Sands et al. [49], Wu, Z. X., & Wei, J. J. [50], and Li, W. J. et al. [51], scores across five dimensions and 25 evaluation items were aggregated and log-transformed. Specific sub-indicators include: environmental philosophy, environmental objectives, environmental management system, environmental education and training, environmental initiatives, environmental incident emergency response mechanisms, environmental honors or awards, “Three Simultaneities” system, pollutant discharge compliance, key pollution monitoring units, sudden environmental incidents, environmental violations, environmental petition cases, ISO 14001 certification status, ISO 9001 certification status, social responsibility reports, annual reports of listed companies, Environmental reports, COD emissions, SO_2 emissions, smoke and dust emissions, CO_2 emissions, industrial solid waste generation, dust and smoke control measures, exhaust gas reduction and treatment, wastewater reduction and treatment, noise, light pollution, radiation control, clean production implementation, solid waste utilization and disposal. In Table 6, the interaction coefficient in Column (2) is 5.344 and significantly positive at the 1% level, indicating that green bonds significantly enhance environmental information disclosure quality, thereby validating the hypothesis of this paper.

MEA represents the level of green awareness among senior executives. Following Zhao, Q. N., & Li, H. [52], management environmental awareness (MEA) is measured using the following method: companies are scored based on whether they disclose their environmental philosophy, environmental

objectives, environmental management system, environmental education and training, environmental initiatives, environmental incident emergency response mechanisms, environmental honors or awards, and the "three simultaneous" system. Each item is worth 1 point, totaling 8 points. As shown in Table 6 Column (3), the coefficient for the explanatory variable is 0.735 and significant at the 1% level, indicating that green bonds effectively enhance executive green awareness levels, thereby validating the preceding hypothesis.

10. Conclusion

Under China's dual carbon goals and high-quality development strategy, assessing the innovative value of green finance for the real economy holds significant practical importance. This paper employs data from Chinese A-share listed companies between 2007 and 2024 to empirically examine the effects of green bond issuance on corporate innovation efficiency. The findings reveal that green bond issuance significantly enhances corporate innovation efficiency. This conclusion remains robust after undergoing a series of stability tests, including PSM-DID, parallel trend tests, placebo tests, changing the dependent variable, and excluding anomalous years. Heterogeneity analysis indicates that this effect is particularly pronounced in non-state-owned enterprises, heavily polluting industries, eastern regions, and large-scale enterprises. Mechanism tests further reveal that green bonds primarily empower corporate innovation through three pathways: alleviating financing constraints, improving environmental disclosure quality, and enhancing executives' green awareness. The findings align with the theoretical mechanism whereby green bonds drive corporate innovation through targeted financing, enhanced environmental transparency, and improved internal governance. The findings of this study not only deepen our understanding of how green finance empowers innovation in the real economy but also provide policy insights for regulators to refine green bond frameworks and for enterprises to leverage green financial tools for innovation-driven transformation.

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