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An Empirical Analysis of the Impact of Green Bonds on Corporate Green Technological Innovation: Evidence from Chinese Listed Companies

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Abstract. Against the backdrop of the ongoing pursuit of the "dual carbon" targets and the rapid development of green finance, green bonds function as a key financing instrument to support corporate low-carbon transitions. Whether enterprises can promote the green technological innovation of their own enterprises is a serious problem at present. Based on a sample of Chinese A-share listed companies in 2014 and 2024, a multi-period DID model is used in this paper to examine the effect of green bond issuance on enterprises' actual green technological innovation and also to conduct moderation and heterogeneity analysis. Based on empirical studies, it has been found that the issuance of green bonds is positively correlated with an increase in the number of green patent applications by companies, and this result is consistent after robustness tests. The geographical distribution of intellectual property protection is also positively associated with the above indicators, and it has been discovered that stronger protection of intellectual property can promote innovation more effectively via green bonds. Heterogeneity analysis shows that, between state-owned enterprises (SOEs) and non-high-tech enterprises, the impact of green bonds on innovation is relatively more pronounced. Therefore, this paper will expand the scope of research on green finance and green technological innovation to provide empirical support and policy suggestions for the optimisation of green bond allocation and the promotion of corporate green transformation.

Keywords: Green bonds, green technological innovation, Chinese listed companies, difference-in-differences model

1. Introduction

As a whole, the world's countries and regions are shifting towards an ecological civilization. China has explicitly set the "30·60" dual-carbon goals, and now green technological innovation is one of the primary ways enterprises can achieve low-carbon development and green, high-quality development [1]. Research and Development in green technology have a long cycle, require large amounts of capital investment, and are high-risk. Most enterprises face severe financing difficulties and cannot continuously support and advance innovation activities [2], so in response, China's green finance system has been developed and matured rapidly. Given that green bonds have a clear use of

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funds, relatively low financing costs and good policy support, they have gradually become one of the means to raise money for green development. Although the scale of the green bond market and policy support have been growing continuously, it has not been clearly shown through comprehensive and rigorous empirical studies whether they can effectively promote corporate green technology innovation, what the specific ways in which they operate are, and what the actual results are. The aforementioned gap is the actual basis of this paper.

A large number of studies have been conducted in previous years on the theoretical basis and microeconomic effects of green bonds and how they work. Based on the theory of signaling and the theory of financing constraints, it can be concluded that green bonds can reduce information asymmetry and alleviate corporate financing constraints by providing funds at a lower cost over an extended period [3, 4]. In terms of research methods, most foreign scholars have employed event studies and pricing analysis [5], and at the same time, most Chinese scholars have chosen multi-period DID, PSM-DID and mediation effect models [6], because they are more suitable for China's policy-driven institutional environment. In terms of the link between green bonds and green technological innovation, both abroad and in China, it is generally believed that enterprises issuing green bonds can motivate an increase in the quantity of green patents and improve their technical level through an increase in R&D investment, adjustment of debt maturity structure, enhanced information transparency, etc. The above effect is more obvious in the case of state-owned enterprises, high-polluting industries and financing-dependent enterprises [7]. At the same time, there are still many deficiencies in the existing research; most of the mechanism tests have been carried out at the level of financing channels, and the deeper transmission path has not been fully explored. Research based on the Chinese context mainly focuses on evaluating the effects of policies, and international studies are more concentrated on market mechanisms and premium effects; there is a lack of integration between the two. The problem of long-term dynamic effects and supply chain spillover is still to be solved.

The focus of this paper is the effect of green bonds on the green technological innovation of enterprises, and based on the theory of externalities and the theory of technological innovation, an analysis will be conducted. Green technological innovation has two positive externalities; that is, the private benefit is lower than the social benefit, so there is a market under-supply and a theoretical basis for the intervention of green bonds. Through targeted financial assistance, policy incentives and external supervision, green bonds are given the right to monitor for the purpose of promoting green innovation; therefore, this paper proposes the main hypothesis that, all other things being equal, the issuance of green bonds can promote corporate green technological innovation to a certain extent. At the same time, the level of regional intellectual property protection and corporate agency costs are also factors that can moderate this effect; that is to say, stronger protection of intellectual property and lower agency costs will enhance the promoting effect of green bonds on innovation. Based on the above hypotheses, an empirical design will be carried out in this paper to uncover their reasons and limitations.

It is good for research and life. Theoretically, green bonds can be used to study how they affect the mechanism of green technological innovation in empirical research, and this paper hopes to address the problems of research in green finance in isolation and micro-level corporate innovation behaviour. It provides an update to the theoretical system supporting the development of green finance in promoting the structural adjustment of the real economy and adds new theoretical content to the study of drivers of corporate green innovation. Practically speaking, the results can offer some references for listed companies to optimise their green financing structure and boost the efficiency of innovation decision-making; thus, they will be better able to tackle funding problems for

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innovation and strengthen their green competitiveness. At the same time, they provide empirical data to help policymakers improve the green bond market and optimise the incentive mechanism; thus, funds can be directed to support the green innovation sector, advance the implementation of the "dual-carbon" goals, and promote high-quality development of the green economy.

2. Empirical strategy

2.1. Data and sample construction

The research sample is the list of A-share listed companies in China from 2014 to 2024, and the data are obtained from the CSMAR and CNRDS databases. The financial sector, ST/ST companies and samples with missing core variables are not included in this study, and continuous variables are trimmed at the 1st and 99th percentiles. Finally, there are 35,850 firm-year observations in the dataset, and it is an unbalanced panel data structure.

2.2. Model specification and variable definition

Table 1. Variable definitions

Variable Type	Variable Name	Variable Symbol	Measurement Method
Dependent Variable	Substantive Green Technology Innovation	lnGrein1	Natural log of the volume of green patent applications +1
Key Explanatory Variables	Green bond issuance	GB×post	Coded as 1 in the issuance year and post-treatment periods; 0 in pre-issuance years.
Control variables	Intellectual Property Protection	Protect	Regional technology market turnover / regional GDP
	Company Size	Size	Natural log of year-end all assets
	Debt-to-Equity Ratio	Lev	Aggregate year-end debt obligations / gross assets
	Return on Gross Assets	ROA	Net Income / gross Assets
	Revenue Growth Rate	Growth	Increase in Revenue / Previous Year's Revenue
Control variables	Operating Cash Flow	Cash Flow	Net Cash Flow from Operating Activities / gross Assets
	Tobin's Q	Tobin Q	Firm Market Value A / gross Assets
	Management Shareholding	Mshare	Percentage of Total Shares Held by Directors, Supervisors, and Senior Management
	Board Size	Board	Natural logarithm of the number of board members
	Dual Role	Dual	An indicator taking the value of one upon the combination of chairman and CEO roles within a single manager, and zero otherwise.

The purpose of this paper is to study whether the issuance of green bonds by enterprises promotes actual green technological innovation. A staggered difference-in-differences model is used, and the

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first issuance of green bonds is considered an exogenous shock to solve the endogeneity problem [8]. The Model is as follows:

$$lnGrein1_{it}=\alpha+\beta GBpost_{it}+\gamma X_{it}+\mu_i+\lambda_t+\varepsilon_{it} \quad (1)$$

Subscript i stands for each firm and t refers to the corresponding sample year. μ_i and λ_t represent firm-specific and year-specific fixed effects, respectively; and ε_{it} denotes the random error term.

$lnGrein1_{it}$ represents substantive green technological innovation. Green invention patents better reflect high-quality, substantive technological breakthroughs; therefore, this study uses the natural logarithm of firm i's green invention patent applications in year t + 1 as a proxy for the firm's level of substantive green technological innovation [9]. $GBpost_{it}$ is green bond issuance (multi-period DID interaction term) $GBpost_{it} = GB_i \times post_{it}$. Here, GB_i is an individual dummy variable; if firm i issued green bonds during the sample period, it is classified as the treatment group and takes the value 1, otherwise, 0; $post_{it}$ is a time dummy variable; if firm i issued green bonds for the first time in year t or later, it takes the value 1, and 0 for years prior to issuance. The core coefficient β reflects the net effect of green bond issuance on firms' substantive green innovation. Table 1 summarizes the concrete definition of each variable.

2.3. Descriptive statistics

Table 2 presents the mean of lnGrein1 is 0.239, indicating significant differences in green innovation across firms; the mean of GBpost is 0.018, consistent with the characteristics of a policy shock; and the mean of Protect is 0.037, suggesting differences in the regional innovation institutional environment. All control variables fall within reasonable ranges, and the sample distribution meets expectations.

Table 2. Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
lnGrein1	35,850	.239	.58	0	2.996
GBpost	35,850	0	.018	0	1
Protect	35,850	.037	.044	0	.184
Size	35,850	22.229	1.24	19.932	26.188
Lev	35,850	.417	.201	.059	.894
ROA	35,850	.029	.067	-.27	.191
Growth	35,850	.129	.363	-.582	2.068
CashFlow	35,850	.047	.067	-0.155	.239
TobinQ	35,850	2.085	1.354	.828	8.782
Mshare	35,850	.146	.193	0	.678
Board	35,850	2.097	.194	1.609	2.565
Dual	35,850	.319	.466	0	1

2.4. Correlation analysis and multicollinearity test

GBpost is significantly positively correlated with lnGrein1 at the 1% level, providing preliminary support for the research hypothesis; Protect is significantly positively correlated with lnGrein1,

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while financing constraints are significantly negatively correlated with lnGrein1, consistent with theoretical expectations. All variables yield absolute correlation coefficients below 0.7, pointing to negligible serious multicollinearity concerns.

Based on the results of the Variance Inflation Factor (VIF) test, all VIF values are much smaller than 10, and the mean is only 1.26; thus, it can be concluded that there is no serious multicollinearity among the explanatory variables and the selection of variables for the model is reasonable.

3. Empirical testing and mechanism analysis

3.1. Baseline regression

After adding individual and annual fixed effects, the estimation results are presented in Table 3. The coefficient for GBpost is positive and statistically significant at the 1% level; thus, it can be concluded that green bond issuance promotes substantial green innovation and thus supports H1. Green bonds will help enterprises extend the period for making high-risk, long-term investments in green R&D and increase the output of green invention patents.

Table 3. Baseline regression

	(1)	(2)
	lnGrein1	lnGrein1
GBpost	0.57436***	0.58192***
	(4.62)	(4.69)
Size		0.04088***
		(7.00)
Lev		0.00411
		(0.18)
ROA		0.13617***
		(3.03)
Growth		-0.01292**
		(-2.11)
Cash Flow		-0.02548
		(-0.65)
TobinQ		0.00724***
		(2.83)
Mshare		0.06432**
		(2.12)
Board		-0.07150***
		(-3.36)
Dual		-0.00686
		(-0.97)
Id	yes	yes
year	yes	yes
_cons	0.23905***	-0.54488***

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Table 3. (continued)

	(126.79)	(-4.08)
N	35,850	35,850
R^2	0.678	0.679

3.2. Parallel trends test

Before the implementation of the policy, there is no significant difference in the number of green invention patent applications between the treated and control groups, as shown in Figure 1. The coefficients for the year of issuance and subsequent years were significantly positive; that is to say, the promotional effect of green bonds on green innovation has lasted for at least two years after issuance and continues to strengthen.

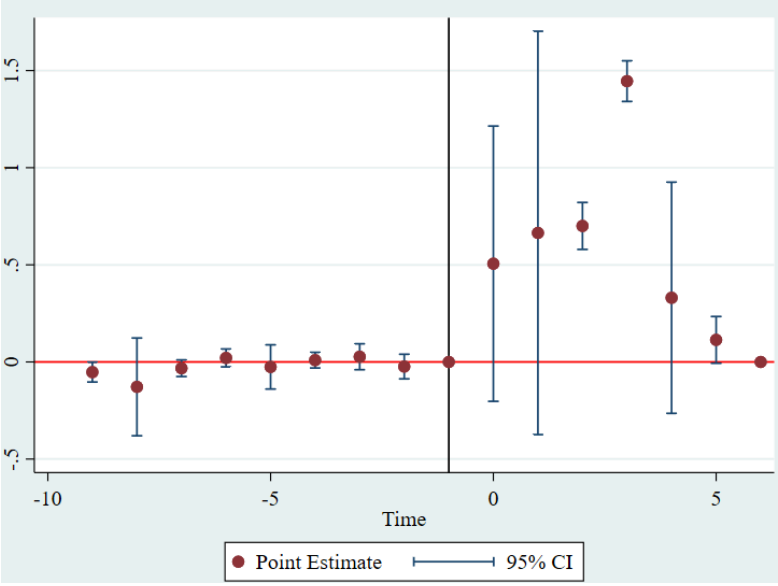

Figure 1. Parallel trends test (image credit: original)

3.3. Robustness tests

First, to account for the lagged effect of policies, carried out a regression using the core explanatory variable (green bond issuance) lagged by two periods (L2.GBpost). As shown in Table 4, the coefficient is 0.921 and is significant at the 5% level; thus, it can be concluded that the promotional effect of green bonds on green innovation is both persistent and has a lag effect, thus supporting the above conclusions.

Secondly, the dependent variable will be replaced with "the logarithm of green utility patent applications plus one" to represent the output of innovation. As shown in the regression results, the estimated coefficient of green bond issuance (GBpost) is 0.492. The first one is the same.

Finally, to reduce the sample size, the data from the 2019-2021 pandemic period were omitted, and then the regression was run again. As shown in the results, the coefficient of green bond issuance (GBpost) is 0.547 and is thus highly reliable.

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Table 4. Robustness tests

	Two-period lag	Replacing the Dependent Variable	Reduced Sample Size
	lnGrein1	lnGrein2	lnGrein1
L2.GBpost	0.92139**		
	(2.16)		
GBpost		0.49209***	0.54742***
		(3.24)	(4.03)
Size	0.04121***	0.05046***	0.04460***
	(5.04)	(7.05)	(6.68)
Lev	0.01887	-0.00988	-0.00588
	(0.61)	(-0.35)	(-0.22)
ROA	0.11018**	0.15679***	0.16686***
	(2.08)	(2.85)	(2.93)
Growth	-0.00221	-0.01354*	-0.01071
	(-0.29)	(-1.81)	(-1.46)
CashFlow	-0.07405	-0.05011	-0.01882
	(-1.52)	(-1.05)	(-0.40)
TobinQ	0.01029***	0.00758**	0.00774**
	(2.90)	(2.42)	(2.40)
Mshare	0.11086**	0.11823***	0.09351***
	(2.52)	(3.19)	(2.64)
Board	-0.06984**	-0.07198***	-0.07853***
	(-2.55)	(-2.76)	(-3.11)
Dual	-0.00250	-0.00966	-0.00251
	(-0.28)	(-1.11)	(-0.29)
Id	yes	yes	yes
year	yes	yes	yes
_cons	-0.58229***	-0.64524***	-0.62323***
	(-3.10)	(-3.94)	(-4.06)
N	24,503	35,850	25,997
R^2	0.697	0.703	0.685

3.4. Testing of moderation mechanisms

As shown in Table 5, the interaction term between intellectual property protection and GBpost boasts a positive coefficient significant at the 1% level, illustrating that regional intellectual property protection exerts a positive moderating effect [10]. Stronger protection plays a more notable promoting role in green bonds in innovation. Robust intellectual property protection safeguards the returns on corporate innovation and reinforces the guiding effect of green bonds on R&D investment.

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$$lnGrein1_{it}=\alpha+\beta_1 GBpost_{it}+\beta_2 Protect_{it}+\beta_3(GBpost_{it}\times Protect_{it})+\gamma X_{it}+\mu_i+\lambda_t+\varepsilon_{it} \quad (2)$$

Table 5. Moderation mechanism test

	(1)	(2)
	lnGrein1	lnGrein1
GBpost	0.58774***	1.67586***
	(4.73)	(5.88)
Protect	0.31064*	0.33553*
	(1.68)	(1.81)
Protect*GBpost		63.61462***
		(4.24)
Size	0.04047***	0.04020***
	(6.92)	(6.88)
Lev	0.00388	0.00316
	(0.17)	(0.14)
ROA	0.13608***	0.13516***
	(3.03)	(3.01)
Growth	-0.01281**	-0.01264**
	(-2.09)	(-2.07)
Cash Flow	-0.02486	-0.02443
	(-0.64)	(-0.63)
TobinQ	0.00736***	0.00725***
	(2.88)	(2.84)
Mshare	0.06287**	0.06282**
	(2.07)	(2.07)
Board	-0.07107***	-0.07094***
	(-3.34)	(-3.34)
Dual	-0.00703	-0.00702
	(-0.99)	(-0.99)
Id	yes	yes
year	yes	yes
_cons	-0.54809***	-0.54293***
	(-4.10)	(-4.07)
N	35,850	35,850
R^2	0.679	0.679

3.5. Heterogeneity analysis

According to the heterogeneity analysis results in Table 6, the promotional impacts of green bond offerings on enterprises' substantive green technological innovation vary significantly across different types of enterprises. In terms of ownership structure, green bonds exert prominent

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facilitating impacts on SOEs' green innovation, with no equivalent effect observed in non-state-owned firms [11]. SOEs have strong policy implementation capabilities and can utilize green bonds more efficiently to drive innovation. In terms of industry attributes, the promotional effect is stronger for non-high-tech enterprises; high-tech enterprises have ample innovation resources, so the marginal effect of green bonds is small. Non-high-tech enterprises have a strong need for transformation, making the financing incentive effect of green bonds more pronounced.

Table 6. Heterogeneity analysis

	Non-SOEs	SOEs	Non-High-Tech	High-tech
	lnGrein1	lnGrein1	lnGrein1	lnGrein1
GBpost	0.00500	0.60446***	0.69455***	0.42480*
	(0.01)	(4.47)	(5.19)	(1.76)
Size	0.04975***	0.01867*	0.02582***	0.06062***
	(6.95)	(1.71)	(3.35)	(6.88)
Lev	-0.00984	0.05105	0.00685	0.01855
	(-0.36)	(1.05)	(0.22)	(0.54)
ROA	0.12127**	0.04192	0.06712	0.16454***
	(2.43)	(0.39)	(1.11)	(2.59)
Growth	-0.01642**	-0.01191	-0.00147	-0.02368**
	(-2.32)	(-0.96)	(-0.20)	(-2.54)
CashFlow	-0.03018	0.01802	-0.05566	0.01187
	(-0.66)	(0.24)	(-1.15)	(0.21)
TobinQ	0.00696**	0.00864	0.00299	0.00973***
	(2.45)	(1.42)	(0.81)	(2.79)
Mshare	0.00891	0.03397	0.10954**	0.04518
	(0.27)	(0.14)	(2.38)	(1.11)
Board	-0.05330**	-0.09404**	-0.06798**	-0.06330**
	(-2.09)	(-2.24)	(-2.47)	(-2.07)
Dual	-0.01050	0.00711	0.00579	-0.01389
	(-1.31)	(0.43)	(0.61)	(-1.40)
Id	yes	yes	yes	yes
year	yes	yes	yes	yes
_cons	-0.77028***	0.01719	-0.31853*	-0.93973***
	(-4.77)	(0.07)	(-1.80)	(-4.69)
N	25,563	10,287	13,451	22,399
R^2	0.660	0.730	0.661	0.682

4. Conclusion

Based on a sample of Chinese A-share listed companies from 2014 to 2024, a multi-period DID model will be employed in this paper to examine the effect of green bond issuance on the actual green technological innovation of these companies empirically. It has been found that green bond

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issuance is correlated with an increase in the number of green patent applications by enterprises. After the robustness test, it was still the same after adding a lag effect, substituting the dependent variable and excluding samples during the pandemic period. At the level of mechanism, regional intellectual property protection is a positive moderator; that is to say, as the level of protection increases, the innovation-stimulating effect of green bonds is also strengthened. From the heterogeneous analysis, it can be seen that the promotional effect of green bonds is relatively stronger for state-owned listed companies and non-high-tech enterprises. State-owned enterprises are strong in implementing policies, and non-high-tech enterprises need to make more changes; thus, they are in a better position to promote green innovation with the help of green bonds. In short, green bonds can help financing-constrained enterprises obtain support and external supervision for high-quality green technological innovation. Thus, it can be concluded that green finance promotes the low-carbon development of enterprises in the real economy.

Based on the above results, recommendations are put forward for enterprises, the market and policies, as well as directions for future research. The company should make full use of green bonds to improve its financing structure, expand investment in green technological research and development, and boost the efficiency of innovation commercialisation. At the policy level, it is necessary to strengthen the standards and regulatory systems for green bonds, improve supervision of the use of funds, enhance intellectual property protection, strengthen the incentive effect of green finance, etc. In the future, more research can be conducted to explore the underlying transmission mechanisms of green bonds promoting green innovation, as well as long-term dynamic changes and supply chain spillover effects, and cross-national and cross-industry comparisons can be made under the influence of international market mechanisms and China's policy environment to provide richer theoretical and empirical support for the high-quality development of the green finance system.

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