

## Article

# Financing Green Technological Innovation: The Role of Local Government Debt in China

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## Abstract

Effectively harnessing the productive potential of local government debt while mitigating financial risks is critical for urban sustainable development. Focusing on the standardized development phase of local government debt in China, this study examines how local government debt affects green technological innovation using Chinese A-share listed firms from 2015 to 2021. We find that regulated explicit debt significantly promotes firms' green innovation through three channels: green bond issuance, digital infrastructure investment, and improved firm profitability. In contrast, implicit debt exerts a nonlinear inhibitory effect, with significant negative impacts only after a threshold is exceeded. Heterogeneity analysis shows stronger effects in developed regions, areas with more optimized industrial structures, and state-owned, large, and high-ESG firms. Our findings suggest that optimizing debt structure and directing funds to productive green and digital sectors can effectively drive urban green innovation.

**Keywords:** local government debt; urban governance; green technological innovation; green bonds; digital infrastructure

## 1. Introduction

Urban economic development is often constrained by government financing gaps [1–3], which can be alleviated by local government debt [4–6]. With the rise of Keynesian economics, major market economies have increasingly expanded government debt to increase the supply of public goods and infrastructure investment, thereby offsetting insufficient effective demand and fostering steady economic growth. In response to the global financial crisis, the Chinese government implemented a ‘four trillion investment’ stimulus package, with 70.5% of the investment funded by local governments. However, excessive local government debt can hinder economic growth by crowding out private investment and reducing public expenditure, posing a significant latent risk to financial systems and potentially jeopardizing long-term economic prospects [7–9]. Therefore, many countries have implemented measures to regulate and manage local government debt to mitigate risks of currency devaluation and government debt default [10], such as Switzerland’s debt brake in 2002 [11], Germany’s debt brake in 2009 [12], and China’s systematic governance reform of local government debt. Effectively harnessing the positive externalities of local government debt while minimizing associated debt risks is crucial for ensuring the effectiveness of urban governance and promoting the sustainable growth of urban economies.



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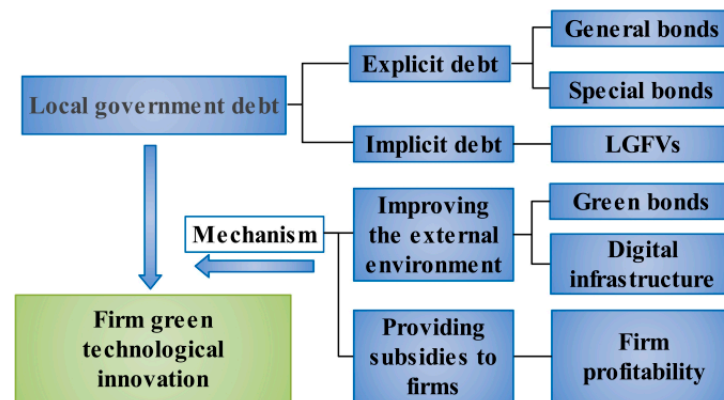
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Over the past two decades, emerging economies have experienced remarkable economic growth. However, this rapid development has led to resource scarcity and environmental degradation, posing significant challenges to further economic progress [13]. In response to environmental degradation and climate change, researchers worldwide have explored sustainable development policies [14]. The key to implementing such strategies lies in balancing ecological health and economic growth [15]. Recent evidence from resource-intensive economies further demonstrates that energy intensity and CO<sub>2</sub> emissions significantly constrain long-term economic growth, underscoring the urgency of transitioning toward sustainable development [16]. As the world's largest CO<sub>2</sub> emitter, China has committed to peaking its carbon dioxide emissions by 2030, a goal known as "carbon peaking," and achieving carbon neutrality by 2060, meaning that greenhouse gas emissions will be balanced by absorptive capacity. This ambitious target highlights China's urgent challenge of reducing environmental pollution while achieving sustainable development alongside economic growth. Unlike traditional innovation, green technological innovation aims to maximize innovation output while minimizing factor inputs and environmental costs [17], thereby linking economic and environmental benefits. Therefore, fostering green technological innovation is essential for promoting cleaner production processes and green innovation, reducing reliance on fossil fuels, curbing emissions of pollutants such as CO<sub>2</sub> [18], and driving green economic growth [19]. As a public good, the supply and consumption of the ecological environment are shaped by governance within a jurisdiction [20]. Improving innovation capabilities requires not only market incentives to stimulate innovation actors and elements but also government efforts to rationally allocate public resources, continually optimize the factor and institutional environments, and strengthen innovation governance capacity [21–23].

In this context, governments need to increase investment in green technological innovation and environmental protection to develop a green economy, which raises government spending in the short term [24] and widens the funding gap. Moreover, emerging research indicates that fiscal spending strategically directed toward green innovation can effectively chart a path toward sustainable development, underscoring the productive role of government expenditure in environmental transition [25]. Consequently, local governments often resort to borrowing to bridge this gap and better fulfill their governmental functions [26,27]. Therefore, it is worthwhile to examine the impact of local government debt on green technological innovation. This study makes three key departures from the existing literature, particularly Chen et al. [28]: First, we focus exclusively on the standardized governance period of local government debt (2015–2021), during which explicit bonds have become the main formal financing instrument for local governments, with proceeds mainly invested in productive public projects. Second, we explicitly distinguish between explicit debt (general and special bonds) and implicit debt (LGFVs), revealing their fundamentally different impacts on green innovation. Third, we identify and empirically verify three productive transmission channels through which explicit debt promotes green innovation, rather than focusing solely on the crowding-out mechanism. Our study focuses on new categories of debt, including general debt, special debt, and LGFVs (local government financing vehicles). Drawing on Brixi's [29] fiscal risk matrix, we categorize local government debt, including general and special debt, and implicit debt, represented by LGFVs, according to responsibility and obligation. We examine their heterogeneous impacts on green technological innovation using matched city-level debt data and A-share listed firm data from 2015 to 2021. To address potential endogeneity issues, we employ two instrumental variables: the proportion of land conveyance fee revenue to fiscal revenue and the fiscal self-sufficiency rate. Mediation analysis reveals that explicit debt promotes green innovation through green bond issuance, digital infrastructure investment, and improved firm profitability. Implicit

debt, by contrast, exerts a nonlinear inhibitory effect with significant negative impacts emerging only after a threshold is exceeded (Figure 1).



**Figure 1.** Main research content.

Our core theoretical contribution is to resolve conflicting findings in the literature by showing that debt structure and debt use, rather than debt level per se, determine the impact on green innovation. This overarching contribution is reflected in four specific dimensions.

First, we reconcile the debate on local government debt and green innovation. Contrary to the crowding-out effect documented by Chen et al. [28], we demonstrate that local government debt exerts a significant positive impact on corporate green innovation. By distinguishing explicit productive debt from implicit opaque debt, we provide a nuanced and systematic explanation for the heterogeneous effects observed in previous empirical studies, clarifying that the divergent conclusions in the existing literature stem primarily from the failure to differentiate debt types and uses. Second, we enrich the literature on the economic consequences of government debt by shifting the focus from macroeconomic growth to firm-level green transition outcomes. Prior studies have extensively debated the growth effects of government debt [5,6,8]; however, few have examined its implications for environmental performance at the firm level. Our findings show that productive government debt can generate positive environmental externalities, extending fiscal policy research into the sustainability domain. Third, we identify two novel transmission channels linking local government debt to green innovation: green bond financing and digital infrastructure spillovers. While the existing green innovation literature emphasizes environmental regulation and direct government subsidies [14,15,18], we show that indirect public investment through debt financing can also effectively stimulate corporate green innovation. This broadens the understanding of institutional drivers of green innovation. Fourth, we contribute to the digital infrastructure literature by examining its ecological effects. Previous studies have predominantly focused on the economic impacts of digital infrastructure [30], while largely neglecting its environmental implications. Our findings demonstrate that digital infrastructure investment significantly mediates the debt–innovation nexus, suggesting that the “new infrastructure” strategy can serve as a dual-purpose tool for economic digitalization and ecological modernization. Fifth, we provide empirical evidence of the nonlinear threshold effect of implicit debt on green innovation. We show that moderate implicit debt does not significantly harm green innovation, but excessive LGFV borrowing creates systemic financial risks and crowds out corporate financing. This finding has important implications for the governance of implicit debt.

The remainder of this paper is organized as follows. Section 2 presents the background and hypothesis development. Section 3 describes the data and empirical strategy. Section 4 presents the results, and Section 5 concludes the paper.

## 2. Background and Hypothesis Development

### 2.1. Local Government Debt in China

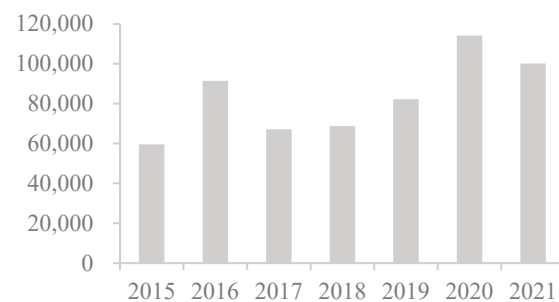
Before the 2008 financial crisis, the expansion of local government implicit debt in China was primarily shaped by two institutional factors. First, China's 1994 tax-sharing reform created a mismatch between local fiscal power and administrative responsibility. Second, the old Budget Law restricted the legal financing channels available to local governments [31]. Consequently, local governments faced growing financing needs and widening fiscal imbalances. Unlike municipal governments in the United States, Chinese local governments lack the authority to collect sales, property, or income taxes. As a result, local governments turned to borrowing to bridge the fiscal gap and strengthen governmental functions [26,27].

Following the 2008 financial crisis, the Chinese government introduced a “four trillion investments” stimulus package and relaxed restrictions on local governments through LGFVs under the old Budget Law. This stimulus package was the primary driver of the sharp increase in implicit debt among Chinese local governments. Bai et al. estimated that by the end of 2010, 72.8% of the actual expenditure under the “four trillion investments” package was financed through off-balance-sheet LGFVs. Moreover, the large scale, diverse forms, and complex debt relationships associated with local government implicit debt, particularly local government financing vehicles (LGFVs), pose significant risks and supervisory challenges [31,32]. LGFVs inhibit firm innovation and have long-term effects on economic growth by squeezing financial resources available to firms [33].

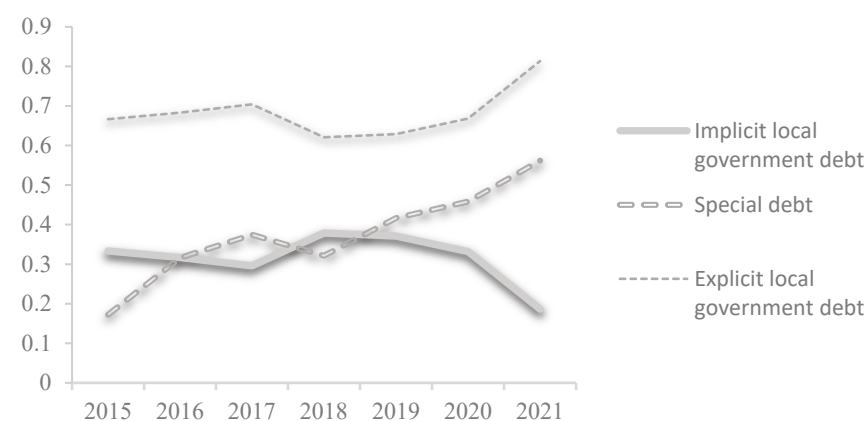
To curb the disorderly expansion of local government debt, especially implicit debt, China has progressively strengthened its local government debt governance system, by introducing a series of supporting policies including the revised Budget Law, the Opinions on Strengthening Local Government Debt Management, and the Decisions on Deepening the Reform of Budget Management System. These policies constitute a major institutional adjustment to the local government debt governance framework, encompassing three core aspects. Firstly, local governments were formally authorized to issue debt through bonds, while irregular borrowing through institutions such as financing platforms was explicitly restricted. The policy framework aims to gradually standardize the financing behavior of local governments and clarify the boundaries of government debt obligations. Debt incurred through non-statutory channels or in disguised forms is no longer recognized as formal government debt and is instead categorized as implicit debt [31]. Meanwhile, special bonds were formally introduced as a new type of explicit local government debt, while urban investment debt issued by LGFVs remains a common form of implicit debt. Secondly, local government borrowing is subject to unified quota management. Each province, autonomous region, and municipality directly under the central government must submit proposed government debt limits to the Ministry of Finance, which then submits them to the State Council for approval. General debt revenue and expenditure are incorporated into general public budget management, while special debt revenue and expenditure are incorporated into government fund budget management. Relevant expenditures in government–social capital cooperation projects are included in the corresponding government budget according to their nature, forming a dual management system of debt limits and budget constraints. Thirdly, these measures clarify the primary responsibility of local governments for debt repayment and strengthen budget constraint mechanisms, to mitigate moral hazard in local government borrowing. Furthermore, early warning and emergency response mechanisms for local government debt risks have been introduced, to improve the rigor of debt risk prevention and resolution.

Figure 2 depicts the scale and structural changes of local government debt in China from 2015 to 2021, a period when the above-mentioned debt governance policies were

gradually implemented. Notably, local government debt shows an overall upward trend during this period, driven by China's ongoing economic development. The surge in debt in 2016 was triggered by the disclosure of government debt information, particularly implicit local government debt, as mandated by debt governance. The spike in debt in 2020 can be attributed to increased health expenditures by local governments in response to public health emergencies, which further widened the funding gap. Moreover, Figure 3 illustrates changes in the structure of local government debt. The average share of implicit local government debt in total debt issuance gradually decreased from 2015 to 2017. Concurrently, the average issuance of explicit local government debt, particularly special debt, showed a significant upward trend during this period, indicating a shift in financing needs from implicit to explicit channels. Figure 3 reveals a preliminary optimization of the debt structure. However, historical accumulation means that governments still hold substantial in platform company loans, bond issuances, and trust financing projects. Furthermore, governments have the ability to incur debt through via non-public financial channels, PPP models, government investment funds, and government procurement services. Notably, the proportion of implicit local government debt issued in 2018 saw a significant increase compared to the previous three years, followed by a marked decline from 2019 to 2021.



**Figure 2.** Changes in the scale of local government debt financing in China from 2015 to 2021 (CNY 100 million).



**Figure 3.** The average issuance ratio of various types of local government debt in China from 2015 to 2021.

## 2.2. Green Bonds

Green bonds are bonds whose proceeds are specifically allocated to projects with environmental benefits. While they share the same financial characteristics as traditional bonds, they also incorporate a green or sustainable element. Despite the rapid expansion of the green bond market, the definition of green bonds remains contested [34]. Currently, the “Green Bond Principles (GBP)” established by the International Capital Market Association (ICMA) [35] and the “Climate Bond Standard (CBS)” developed by the Climate Bonds

Initiative (CBI) [36] are the two main internationally accepted standards for defining green bonds. Other international standards include the EU Green Bond Standard proposal [37], the ASEAN Green Bond Standards [38], Japan's Green Bond Guidelines [39], and India's Green Bond Disclosure and Listing Requirements [40]. In 2022, China introduced the "China Green Bond Principles", which define green bonds as securities issued in accordance with legal procedures with proceeds specifically used to support green industries, projects, or economic activities that meet prescribed conditions, while ensuring the repayment of principal and interest as agreed.

In China, "bonds aligned with green" refers to bonds issued before 1 July 2021, whose use of proceeds aligns with at least one of the following standards: the "Green Bond Endorsed Project Catalogue (2015 Edition)" [41], "Green Bond Guidelines" [42], ICMA's "Green Bond Principles" [35], or CBI's "Climate Bond Standard" [36]. For bonds issued after 1 July 2021, the use of proceeds must comply with at least one of the following standards: the "Green Bond Endorsed Project Catalogue (2021)" [43], ICMA's "Green Bond Principles" [35], or CBI's "Climate Bond Standard" [36]. Additionally, the share of funds allocated to green industry projects within the bond's proceeds should not be lower than the requirements for labeled green bonds. If there is insufficient information about the use of proceeds to determine a bond's green attributes, the issuer's primary revenue from green industries should account for at least 50%. This study utilizes the China Bond Green Bond Environmental Benefit Information Database to collect detailed information on "bonds aligned with green" issued from 2015 to 2021 and to calculate their issuance amounts at the city level.

### 2.3. Digital Infrastructure

While traditional infrastructure, such as roads and buildings, contributes positively to economic development [44–47], it is often associated with high carbon and resource intensity, posing significant challenges to urban sustainability [48,49]. In response to worsening environmental conditions and escalating climate change, several economies are redefining their infrastructure strategies to prioritize sustainability. In this context, the Chinese government introduced the "new infrastructure" initiative at the 2018 China Central Economic Work Conference, to harness the potential of the digital technology revolution and industrial transformation. This initiative encompasses three primary components, as defined by the National Development and Reform Commission of China: information infrastructure, fusion infrastructure, and innovation infrastructure. Among these, information infrastructure constitutes the core of digital infrastructure, encompassing next-generation information technologies such as 5G, the Internet of Things, and Satellite Internet systems, as well as computational infrastructure like data centers and intelligent computing centers. As digital infrastructure is a key category within new infrastructure, this paper measures it in terms of investment and effectiveness using indicators such as fixed-asset investment, the density of long-distance optical fiber cables, and internet penetration rates.

### 2.4. Hypothesis Development

To formalize the mechanisms through which local government debt affects firm-level green technological innovation, we develop a theoretical model that integrates fiscal policy, firm innovation decisions, and environmental externalities. Consider a closed economy consisting of local governments and firms. The model operates in discrete time with an infinite horizon. Local governments issue debt to finance public investment, while firms engage in green technological innovation to maximize profits.

The local government faces the following budget constraint:

$$G_t + (1 + r)D_{t-1} = T_t + D_t + F_t$$

where  $G_t$  represents government spending on productive infrastructure (including green bonds and digital infrastructure),  $D_t$  denotes local government debt issued at time  $t$ ,  $r$  is the interest rate,  $T_t$  represents tax revenue, and  $F_t$  captures land conveyance fees and other fiscal revenues.

Following Brixi's (1998) [29] fiscal risk matrix, we decompose total debt into explicit debt  $D_t^{exp}$  (general and special debt) and implicit debt  $D_t^{imp}$  (LGFVs):

$$D_t = D_t^{exp} + D_t^{imp}$$

Representative firms produce output using the following production technology:

$$Y_{it} = A_{it} \cdot K_{it}^\alpha \cdot L_{it}^{1-\alpha} \cdot \mathcal{E}_{it}^\beta$$

where  $Y_{it}$  is output of firm  $i$  at time  $t$ ,  $K_{it}$  and  $L_{it}$  denote capital and labor inputs, and  $\mathcal{E}_{it}$  represents environmental productivity or green technology stock. The parameter  $A_{it}$  represents total factor productivity (TFP), which is influenced by digital infrastructure and public capital.

The green technology stock evolves according to:

$$\mathcal{E}_{it} = (1 - \delta)\mathcal{E}_{i,t-1} + I_{it}^{green} + \gamma \cdot GB_{ct} + \theta \cdot DI_{ct}$$

where  $I_{it}^{green}$  is firm's own green R&D investment,  $GB_{ct}$  represents green bond issuance at city level  $c$ , and  $DI_{ct}$  denotes digital infrastructure investment. The parameters  $\gamma$  and  $\theta$  capture the spillover effects from public green investments and digital infrastructure on firm's green technological capabilities.

Firms maximize their present value of profits subject to the green technology accumulation equation, where the cost function of green innovation is convex in investment and decreasing in existing green technology stock. The detailed intertemporal optimization problem and the full first-order conditions are relegated to Appendix A.

The cost function is specified as:

$$C(I_{it}^{green}, \mathcal{E}_{i,t-1}) = \frac{\phi}{2} \left( \frac{I_{it}^{green}}{\mathcal{E}_{i,t-1}} \right)^2 \cdot \mathcal{E}_{i,t-1} \cdot \frac{1}{\Psi_{ct}}$$

where  $\Psi_{ct}$  represents the financing environment index, which depends on local government debt:

$$\Psi_{ct} = \Psi_0 + \psi_1 \cdot D_{ct}^{exp} - \psi_2 \cdot (D_{ct}^{imp} - \bar{D})^2 \cdot \mathbb{I}(D_{ct}^{imp} > \bar{D})$$

This specification captures two key features: (1) explicit debt improves the financing environment through productive investments ( $\psi_1 > 0$ ); and (2) implicit debt exerts nonlinear effects, with detrimental effects only when exceeding the threshold  $\bar{D}$ .

The local government maximizes social welfare subject to the budget constraint, where household consumption, the social valuation of environmental quality, and the risk cost of implicit debt are incorporated. The complete dynamic welfare maximization is presented in Appendix A.

The government allocates debt proceeds between green bonds and digital infrastructure:

$$G_t = GB_t + DI_t$$

with the constraint that green bond issuance requires matching funds from special debt:

$$GB_t \leq \mu \cdot D_t^{exp}$$

From the firm's first-order condition with respect to green R&D, we obtain the key partial derivatives that link debt to innovation. The explicit derivation steps are provided in Appendix A. Since  $\frac{\partial \Psi_{ct}}{\partial D_{ct}^{exp}} = \psi_1 > 0$  and  $\frac{\partial GB_{ct}}{\partial D_{ct}^{exp}} > 0$ ,  $\frac{\partial DI_{ct}}{\partial D_{ct}^{exp}} > 0$ , we have  $\frac{\partial \mathcal{E}_{it}}{\partial D_{ct}^{exp}} > 0$ .

The financing environment index  $\Psi_{ct}$  remains constant at  $\Psi_0$  for  $D_{ct}^{imp} \leq \bar{D}$ , but decreases quadratically when the threshold is exceeded. The piecewise derivative derivation is detailed in Appendix A. This creates a kinked relationship between implicit debt and green innovation.

Financial instability in internal financing and unstable investment in innovation funds can abruptly interrupt innovation activities, resulting in substantial losses for firms [50]. Consequently, external financing has become a crucial source of funding for technological innovation. However, an increase in local government debt can heighten demand for capital market financing, particularly when local governments finance through Local Government Financing Vehicles (LGFVs). This scenario limits firms' access to credit and raises interest rates, thereby increasing the cost of external financing [33,51]. Effective governance of local government debt enhances the market's role in credit resource allocation by reinforcing the stringent constraints on local debt and managing both its existing level and growth, thereby alleviating the credit squeeze on firms.

If local government debt primarily funds consumer spending rather than productive capital formation, it undermines economic growth prospects [52]. Conversely, when debt is used for productive inputs, its positive externalities become apparent. Typically, general and special debt issuances finance public welfare projects and are not allocated for recurrent expenditures. For instance, in September 2023, a new special bond issuance totaling CNY 361.934 billion was primarily directed towards infrastructure in industrial parks, social undertakings, and transportation, with respective allocations of 28.17%, 18.64%, and 17.82%. Notably, CNY 114.76 billion was invested in digital infrastructure. Based on this context, we propose:

**H1.** *Local government debt fosters firm-level green technological innovation, and implicit debt has a nonlinear effect on green technological innovation.*

Applying the envelope theorem and chain rule to the firm's value function:

$$\frac{d\mathcal{E}_{it}}{dD_{ct}^{exp}} = \underbrace{\frac{\partial \mathcal{E}_{it}}{\partial GB_{ct}} \cdot \frac{\partial GB_{ct}}{\partial D_{ct}^{exp}}}_{\text{Green Bond Channel}} + \underbrace{\frac{\partial \mathcal{E}_{it}}{\partial DI_{ct}} \cdot \frac{\partial DI_{ct}}{\partial D_{ct}^{exp}}}_{\text{Digital Infrastructure Channel}} + \underbrace{\frac{\partial \mathcal{E}_{it}}{\partial \Psi_{ct}} \cdot \frac{\partial \Psi_{ct}}{\partial \pi_{ct}} \cdot \frac{\partial \pi_{ct}}{\partial D_{ct}^{exp}}}_{\text{Profitability Channel}}$$

Each component is positive under the model assumptions: (1) green bond financing  $\frac{\partial \mathcal{E}_{it}}{\partial GB_{ct}} \cdot \frac{\partial GB_{ct}}{\partial D_{ct}^{exp}} > 0$ ; (2) digital infrastructure  $\frac{\partial \mathcal{E}_{it}}{\partial DI_{ct}} \cdot \frac{\partial DI_{ct}}{\partial D_{ct}^{exp}} > 0$ ; and (3) firm profitability enhancement  $\frac{\partial \pi_{it}}{\partial D_{ct}^{exp}} \cdot \frac{\partial I_{it}^{green}}{\partial \pi_{it}} > 0$ .

While China's local government bonds have historically prioritized conventional infrastructure projects, the share of green bonds has surged in recent years, with an increasing portion of special-purpose bonds (SPBs) directed toward sustainable development sectors. According to the Guiding Opinions on Further Strengthening Financial Support for Green and Low-Carbon Development—jointly issued by seven ministries including the People's Bank of China—local governments are explicitly encouraged to include eco-environmental protection and other green initiatives into the eligible scope of SPB financing. Against this policy backdrop, cities such as Shenzhen and Hainan have pioneered the use of SPBs to fund green transportation systems, marine conservation projects, and related sustainable initiatives, marking a strategic shift in local bond allocations from traditional infrastructure to green transformation. The Shenzhen AI Computing Network Project exemplifies this

evolution: financed through RMB 320 million in SPBs, the project integrated cutting-edge green building technologies to reduce energy consumption by more than 20%. Beyond ensuring long-term operational sustainability, the project has also catalyzed corporate innovation in green technologies, offering a replicable blueprint for how SPBs can drive ecological transition and sustainable growth. Tolliver et al. analyzed the green bond markets in 49 countries from 2007 to 2017 and identified macroeconomic and institutional factors as the primary drivers of green bond market development [53]. Torvanger et al. compared the growth of green bond markets in Norway and Sweden from 2013 to 2019, finding that Swedish financial institutions place greater emphasis on sustainability and corporate sector diversity, resulting in faster growth of the Swedish green bond market compared to that of Norway [54]. According to Agliardi & Agliardi, government tax incentives and increased investor awareness of environmental issues play significant roles in expanding the green bond market. Several scholars suggest that green bonds can enhance both the financial and environmental performance of firms [55]. Gianfrate & Peri found that green bonds can boost investor sentiment and promote stock price growth for firms, as they attract socially responsible capital, alleviate financing constraints, and reduce capital costs [56]. Moreover, due to government support for the green bond market, companies issuing green bonds can receive subsidies, interest reductions, or tax incentives. Additionally, Flammer found that companies issuing green bonds have higher environmental ratings and reduced carbon dioxide emissions, indicating that green bonds can improve environmental performance [57]. Fatica & Panzica compared the environmental performance of green bond issuers with that of traditional bond issuers with similar financial characteristics and environmental ratings, finding that green bond issuers have significantly lower pollution emissions. Emissions reductions are even greater when green bonds undergo external review or meet the requirements of the Paris Agreement [58]. Therefore, local governments are among the principal issuers of green bonds, and there is a synergistic relationship between local government debt and green bonds. A substantial portion of green debt funding is directed toward investments in green projects, thereby facilitating the promotion of green technological innovation within enterprises. Furthermore, recent studies emphasize that green financing mechanisms, including climate-focused fiscal instruments, are increasingly recognized as essential tools for aligning public debt management with long-term sustainability objectives [59]. Empirical evidence also suggests that the expansion of green finance significantly contributes to corporate carbon emission reduction, highlighting the environmental effectiveness of debt-funded green projects [60]. Based on this analysis, we propose:

**H2.** *Local government debt facilitates green technological innovation in firms by encouraging the issuance of green bonds.*

Digital infrastructure directly influences green technological innovation through the advancement and diffusion of green technologies. Information infrastructure enhances information availability, facilitating knowledge spillover, and reducing the cost of regional factor flows related to green technological innovation [61]. With the rapid proliferation of digital technologies, robust information infrastructure supports the development and application of digital technologies such as big data and cloud computing, improving the information application environment and the informatization level of enterprises [30]. Specifically, high-speed internet and advanced communication networks, as core components of information infrastructure, break down geographical barriers and enable firms to access real-time information on green technology trends, environmental regulations, and market opportunities at lower cost, thereby mitigating information asymmetry and stimulating green R&D investment [62]. The densification of long-distance optical fiber

cables and the expansion of internet penetration improve the connectivity and accessibility of digital resources, allowing firms to efficiently acquire, process, and disseminate green knowledge across regions [63,64]. Such infrastructure lowers the search and transaction costs for green technology adoption, enabling firms to identify suitable green solutions and collaborate with innovation partners more effectively [65]. Furthermore, improvement in digital infrastructure creates a conducive external environment for firm innovation, attracts high-tech firms to industrial parks, and fosters industrial agglomeration. Through resource sharing and economies of scale within agglomerated spaces, firms can enhance their green technological innovation capabilities and achieve sustainable development [66,67].

Based on this analysis, we propose:

**H3.** *Local government debt promotes green technological innovation by improving the external environment for firms.*

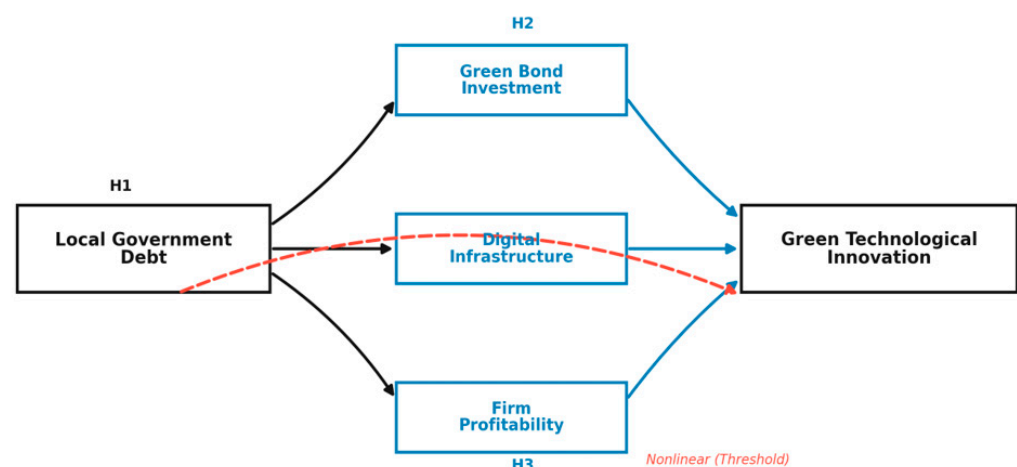
### 2.5. From Theory to Empirical Testing

The theoretical model developed above yields three testable predictions that guide our empirical strategy. It is important to note that the empirical analysis follows a reduced-form approach: the theoretical constructs are mapped to observable proxies rather than structurally estimated, and the model serves as an organizing framework for hypothesis development rather than as a structural model to be estimated directly from the data.

H1 posits that explicit local government debt fosters firm-level green technological innovation by financing productive infrastructure, whereas implicit debt exerts a nonlinear effect once it exceeds a threshold. We test H1 using the benchmark regression (Equation (1)) and the panel threshold regression, using green patent applications as the proxy for green technological innovation. H2 identifies the green bond channel. The model predicts that an increase in explicit debt raises green bond issuance, which in turn expands the green technology stock. We operationalize this channel using the mediation model (Equations (2)–(4)), treating city-level green bond issuance as the mediator.

H3 captures the external environment channel (digital infrastructure) and the internal financing channel (firm profitability). We proxy digital infrastructure with long-distance optical cable density and internet penetration rate, and measure profitability using firm gross revenue. Both are incorporated into the mediation framework to test the external environment mechanism.

Figure 4 summarizes the conceptual linkages between local government debt and firm-level green technological innovation.



**Figure 4.** Conceptual framework: local government debt and green technological innovation.

### 3. Materials and Methods

#### 3.1. Variables

**Dependent variable:** Referring to Chen et al.'s [28] research, we employ the total number of green patent applications and the total number of green invention patent applications by firms as core measures for green technological innovation. In the robustness tests, we utilize the total number of green patent grants and the total number of green invention patent grants by firms as alternative measures. Green patents are identified according to the WIPO Green Patent List and IPC classification codes (e.g., Y02, Y04S). Following standard practice in the innovation literature, we take the natural logarithm of one plus the patent count, i.e.,  $\ln(1 + \text{patents})$ , to accommodate zero values.

**Core independent variable.** Based on the fiscal risk matrix proposed by Brixi [29], we divide local government debt into explicit debt (general debt and special debt) and implicit debt (LGFVs) according to the basis of responsibility and obligation. The baseline regressions employ *lg\_gz*, which measures the stock of explicit local government debt (general and special bonds). Implicit debt (*lg\_fv*), captured by LGFV debt balance, is analyzed separately in Section 4.6 to examine its nonlinear effect. We use the sum of explicit and implicit debt issuance as the total issuance of local government debt. The economic or environmental effects of local government debt may materialize after two to five years. Hence, in the robustness tests, the core explanatory variables in the article also include a two-period lag of local government debt.

Based on the study by Tsang et al. [68], control variables include both firm-level and city-level variables. Firm-level control variables consist of firm age, the shareholding ratio of the largest shareholder, duality of roles, proportion of independent directors, cash-to-total assets ratio, fixed assets-to-total assets ratio, leverage ratio, and the ratio of operating income to previous period's operating income. City-level control variables mainly capture the fiscal revenue level of the city, measured by the proportion of general public budget revenue to GDP.

#### 3.2. Data Sources

As the issuance of special debt began in 2015, this paper has collected and compiled city-level data on the issuance and stock of general debt and special debt at the city level from 2015 to 2021. The data were obtained from public statements of budgets and final accounts issued by local governments. For urban investment debt data, we utilized the Wind database to access information on the debt of local government financing vehicles (LGFVs) and compiled city-level LGFV observations at the city level. We deliberately selected the sample period from 2015 to 2021 for two main reasons. First, 2015 is the earliest year for which explicit debt, consisting of general and special bonds, can be measured consistently, as special bonds were formally launched in that year. Second, although prefecture-level urban investment bond data are available up to 2023, we exclude the years 2022 and 2023 to avoid severe exogenous shocks. These shocks include the lingering effects of the COVID-19 pandemic, a deep adjustment in the real estate sector, and intensive local debt resolution policies. Notable examples include the debt resolution package announced by the Central Political Bureau in July 2023, the allocation of more than RMB 2.2 trillion in bond quotas by the Ministry of Finance, and strict restrictions on new financing for LGFVs. Such shocks would induce atypical fluctuations in debt issuance, fund allocation, and firm innovation behavior, thereby hindering the clean identification of causal effects.

Therefore, this paper selects Chinese A-share listed firms from 2015 to 2021 as samples. The data primarily comes from the CSMAR database and the Chinese Research Data Service (CNRDS) database. We collected annual reports, social responsibility reports, and website information of listed firms to study firm-level green technological innovation. ST

or \*ST firms were excluded from the analysis. To mitigate outlier influence, all continuous variables are winsorized at the 1st and 99th percentiles. All other city-level data are sourced from the “China Statistical Yearbook” and the ‘China Statistical Yearbook on Science and Technology’. Table 1 presents descriptive statistics for the main variables used in the empirical analysis.

**Table 1.** Descriptive Statistics.

| Variables | Explanations                                                    | Obs    | Mean  | Std. Dev. | Min     | Max        |
|-----------|-----------------------------------------------------------------|--------|-------|-----------|---------|------------|
| lg_gz     | Local government debt balance (logarithm)                       | 22,322 | 7.687 | 1.132     | 2.161   | 9.697      |
| lg_fv     | LGFVs debt balance (logarithm)                                  | 23,744 | 6.496 | 1.564     | 0       | 8.923      |
| lg_gsz    | Total number of green patent applications (logarithm)           | 23,744 | 0.456 | 0.913     | 0       | 7.062      |
| lg_gfz    | Total number of green invention patent applications (logarithm) | 23,744 | 0.323 | 0.765     | 0       | 6.746      |
| lg_gps    | Total number of green patent grants (logarithm)                 | 23,744 | 0.728 | 1.063     | 0       | 6.879      |
| lg_gpfs   | Total number of green invention patent grants (logarithm)       | 23,744 | 0.295 | 0.691     | 0       | 6.698      |
| lg_age    | firm age (logarithm)                                            | 23,744 | 2.270 | 0.779     | 0.693   | 3.497      |
| first_p   | Shareholding ratio of the largest shareholder                   | 22,917 | 0.332 | 0.148     | 0.003   | 0.900      |
| tp        | Integration of two roles                                        | 23,370 | 0.307 | 0.461     | 0       | 1          |
| id        | Proportion of independent directors                             | 23,744 | 0.380 | 0.066     | 0.1     | 0.800      |
| ca        | Cash-to-total assets ratio                                      | 23,744 | 0.155 | 0.121     | 0.000   | 0.978      |
| fix       | Fixed assets-to-total assets ratio                              | 23,740 | 0.194 | 0.158     | 0.000   | 0.954      |
| as        | Leverage ratio                                                  | 23,311 | 0.440 | 1.218     | 0.008   | 178.346    |
| re        | Ratio of operating income to previous period's operating income | 23,697 | 4.997 | 391.468   | −10.924 | 59,412.550 |
| in_gdp    | Proportion of general public budget revenue to GDP              | 23,742 | 0.111 | 0.041     | 0.025   | 0.245      |

Measurement rationale for green patent indicators. We employ four complementary indicators to capture firm-level green technological innovation. Green patent applications (including both invention and utility model patents) measure the overall innovative intent and breadth of a firm's green R&D activities in a given year. Green invention patent applications isolate higher-quality innovation, as invention patents are subject to stricter substantive examination requirements regarding novelty and inventive step. Green patent grants and green invention patent grants reflect ex-post approval by patent authorities, representing legally validated technological advances.

We select applications as our baseline measures for two reasons. First, application data more accurately reflect contemporaneous innovation inputs and strategic R&D decisions, whereas grant data are affected by administrative examination lags and discretionary approval processes that often extend two to three years beyond the application date. Second, applications are less susceptible to truncation bias at the end of the sample period, as patents filed in 2021 may not however be granted by 2021. We therefore use grants as robustness proxies because they filter out low-quality or unsuccessful filings, ensuring that our results are not driven by speculative patent applications lacking genuine technological merit. If the positive effect of local government debt persists across both application and grant measures, we can be more confident that the findings reflect real innovation rather than merely patenting propensity.

### 3.3. Empirical Strategy

#### 3.3.1. Baseline Model

In order to test the effect of local government debt on firm-level green technological innovation, we construct the following benchmark regression model:

$$gsz_{ict} = \alpha_0 + \alpha_1 gz_{ct} + \alpha_2 firm\_control_{it} + \alpha_3 city\_control_{ct} + \theta_i + \varphi_t + \varepsilon_{ict} \quad (1)$$

where  $i$ ,  $c$ , and  $t$  represent the firm, city, and year, respectively. Among the terms,  $gsz_{ict}$  denotes the green technological innovation level of firm in a city in a year.  $gz_{ct}$  is local government debt at the city-level.  $firm\_control_{it}$  is the vector of firm-level control variables (firm age, shareholding ratio of the largest shareholder, integration of two roles, proportion of independent directors, cash-to-total assets ratio, fixed assets-to-total assets ratio, leverage ratio and ratio of operating income to previous period's operating income). In addition to the influence of their own characteristics, the green technological innovation activities of firms will also be affected by macro factors such as economic development and financial strength at the city level. Therefore, this paper carries out city control. City-level control mainly focuses on the fiscal revenue level of the city, measured by the proportion of general public budget revenue to GDP.  $\theta_i$  and  $\varphi_t$  represent the firm fixed effect and the year fixed effect, respectively. Further,  $\varepsilon_{ict}$  is the random error term. Coefficient  $\alpha_1$  represents the effect of local government debt on firm-level green technological innovation, which is the most important concern in this article.

#### 3.3.2. Mediation Analysis Model for Mechanism Examination

In line with the approach outlined by Tang et al. [34], this study employs the issuance of green bonds, levels of digital infrastructure and firms' profitability as intermediary variables and constructs mediating effect models to examine the influence mechanism. Initially, city-level intermediary variables, reflecting the level of digital infrastructure, and firm-level intermediary variables, representing firms' profitability levels, are utilized as dependent variables. Meanwhile, local government debt serves as the independent variable to establish the regression model (2).

$$mid_{ict} = \delta_0 + \delta_1 gz_{ct} + \delta_2 firm\_control_{it} + \delta_3 city\_control_{ct} + \theta_i + \varphi_t + \Gamma_{ict} \quad (2)$$

Second, firm-level green technological innovation is used as the dependent variable, and the intermediary variable is used as an independent variable to establish regression model (3).

$$gsz_{ict} = \tau_0 + \tau_1 mid_{ict} + \tau_2 firm\_control_{it} + \tau_3 city\_control_{ct} + \theta_i + \varphi_t + \psi_{ict} \quad (3)$$

Third, firm-level green technological innovation, local government debt and the intermediary variables are included in regression model (4) to observe the change in the local government debt effect.

$$gsz_{ict} = v_0 + v_1 gz_{ct} + v_2 mid_{ict} + v_3 firm\_control_{it} + v_5 city\_control_{ct} + \theta_i + \varphi_t + \kappa_{ict} \quad (4)$$

If the coefficients  $\delta_1$ ,  $\tau_1$  and  $v_2$  are significant, while  $v_1$  becomes smaller or less significant, then the mediating effect exists.

#### 3.3.3. Nonlinear Impact of Implicit Debt

Drawing on the preceding analysis of local government the characteristics of local government hidden debt, it is evident that local government debt can play a crucial role in providing financial support for public infrastructure, thereby improving local infrastructure

development and promoting regional economic growth, which, in turn, can facilitate green technological innovation firm-level green technological innovation. However, a notable portion of local government debt consists of hidden liabilities, notably LGFVs. These hidden debts may lead to inefficient investment and could potentially crowd out corporate financing opportunities. Excessive levels of hidden debt can also affect taxation and currency values through interest rate fluctuations, possibly resulting in distorted tax policies and inflationary pressures.

Furthermore, heightened debt levels may trigger subsequent repayment pressures, thereby exacerbate government credit risk and cause turbulence in financial markets. Additionally, elevated levels of hidden debt can exacerbate uncertainty in fiscal policy and deteriorate the investment climate factors that are detrimental to long-term economic growth and could impede firm-level green technological innovation. It is apparent that the impact of hidden debt on firm-level green technological innovation is nonlinear. To empirically investigate this phenomenon, this chapter employs a panel threshold regression model.

$$gsz_{ict} = \beta_0 + \beta_1 lg\_fv \times I(th \leq \rho_1) + \beta_2 lg\_fv \times I(\rho_1 < th \leq \rho_2) + \dots + \beta_n lg\_fv \times I(\rho_{n-1} < th \leq \rho_n) \\ + \beta_{n+1} lg\_fv \times I(th > \rho_n) + \omega_1 firm\_control_{it} + \omega_2 city\_control_{ct} + \theta_i + \varphi_t + \gamma_{it}$$

where  $th$  represents the threshold variable, measured as the logarithm of LGFVs;  $\rho$  denotes the unknown threshold value;  $n$  represents the number of threshold values;  $I(\bullet)$  denotes the indicator function, equaling 1 if the condition inside the parentheses is met, and 0 otherwise.

## 4. Empirical Results

### 4.1. Baseline Regression Results

The baseline regression results for local government debt on firm-level green technological innovation are presented in Table 2. Column (1) and Column (3) show the results without the inclusion of control variables, while Column (2) and Column (4) include control variables. All regressions incorporate firm fixed effects and year fixed effects. From the regression results in Column (2), it is observed that the impact of changes in local government debt on the total number of green patent applications is positively significant at the 5% level. Specifically, for every 1% change in local government debt, firms' green patent applications increase by 0.016 units, suggesting that local government debt plays a significant role in fostering green technological innovation.

**Table 2.** The effect of local government debt on green technological innovation of firms.

|         | lg_gsz<br>(1)        | lg_gsz<br>(2)         | lg_gfz<br>(3)        | lg_gfz<br>(4)         |
|---------|----------------------|-----------------------|----------------------|-----------------------|
| lg_gz   | 0.036 ***<br>(0.006) | 0.016 **<br>(0.007)   | 0.045 ***<br>(0.005) | 0.027 ***<br>(0.006)  |
| lg_age  |                      | −0.036 ***<br>(0.009) |                      | 0.002<br>(0.007)      |
| first_p |                      | 0.158 ***<br>(0.043)  |                      | 0.123 ***<br>(0.036)  |
| tp      |                      | −0.055 ***<br>(0.014) |                      | −0.034 ***<br>(0.012) |
| id      |                      | 0.006<br>(0.097)      |                      | −0.037<br>(0.081)     |
| ca      |                      | −0.321 ***<br>(0.056) |                      | −0.163 ***<br>(0.047) |
| fix     |                      | −0.056<br>(0.043)     |                      | −0.114 ***<br>(0.036) |

Table 2. *Cont.*

|              | lg_gsz<br>(1) | lg_gsz<br>(2) | lg_gfz<br>(3) | lg_gfz<br>(4) |
|--------------|---------------|---------------|---------------|---------------|
| as           |               | 0.008 *       |               | 0.007         |
|              |               | (0.005)       |               | (0.004)       |
| re           |               | −0.000        |               | −0.000        |
|              |               | (0.000)       |               | (0.000)       |
| in_gdp       |               | 0.753 ***     |               | 0.574 ***     |
|              |               | (0.192)       |               | (0.161)       |
| Constant     | 0.189 ***     | 0.362 ***     | −0.013        | 0.080         |
|              | (0.045)       | (0.069)       | (0.037)       | (0.058)       |
| Firm FE      | YES           | YES           | YES           | YES           |
| Year FE      | YES           | YES           | YES           | YES           |
| Observations | 22,322        | 21,122        | 22,322        | 21,122        |
| R-squared    | 0.002         | 0.006         | 0.004         | 0.006         |

Note: \*, \*\*, and \*\*\* indicate significance at the 10%, 5%, and 1% levels, respectively. Columns (1)–(4) adopt the robust standard error clustered at firm level.

#### 4.2. Endogenous Addressing

A key issue in empirical research is endogeneity mitigation. On the one hand, large-scale local government debt may promote green technological innovation, while improvements in firm-level green technological innovation could, in turn, reduce regional environmental pressure and thereby shrink the scale of productive government expenditure, suggesting a potential reverse causal relationship. On the other hand, numerous unobservable factors may simultaneously affect both local government debt and firm green innovation, raising omitted variable concerns.

To address these endogeneity problems, we employ an instrumental variable (IV) approach and select the proportion of land conveyance fee to revenue as the instrument for local government debt. This choice rests on two conditions. First, with respect to relevance, land conveyance fees constitute a critical source of local government revenue and serve as the principal collateral for debt financing. Following the 1994 tax-sharing reform, local governments increasingly relied on land financing to bridge fiscal gaps, making the share of land revenue a robust predictor of borrowing capacity [26,69]. Mo further shows that jurisdictions with higher land revenue dependence tend to accumulate more debt. Consequently, the instrument satisfies the relevance condition [70].

Second, regarding exogeneity, the cross-city variation in land revenue dependence is largely shaped by historical geographic endowments and predetermined fiscal institutions rather than by contemporaneous firm-level innovation behavior. Local governments' land-conveyance decisions are primarily driven by city-level urban planning, infrastructure needs, and macroeconomic development, not by the innovation behavior of individual firms within their jurisdictions. Therefore, the proportion of land conveyance fee revenue to fiscal revenue affects firm-level green technological innovation primarily through its impact on local government debt, satisfying the exclusion restriction. We acknowledge that land revenue may indirectly influence firm innovation through alternative channels such as urban expansion, industrial structure upgrading, or real estate prosperity. However, these channels operate primarily through the local government's fiscal capacity and borrowing ability, which is precisely the mechanism of local government debt. After controlling for firm fixed effects, year fixed effects, and city-level fiscal variables, any residual influence of land revenue on green innovation that is substantially mitigated. Consequently, the exclusion restriction is satisfied in a conditional sense.

It is evident that a significant correlation exists between land conveyance fees and local government debt. Furthermore, the level of local government land conveyance fee

does not directly correlate with firm-level green technological innovation. Hence, the land conveyance fee serves as a valid instrumental variable. The regression results from the instrumental variable method are presented in Table 3. By selecting the proportion of land conveyance fee to local government fiscal revenue as the instrumental variable, the first-stage regression results demonstrate a significantly positive impact on local government debt financing, suggesting that land conveyance fee indeed enhances the borrowing capacity of local governments. In the second stage, the results reveal that local government debt positively influences the number of applications for green patents and green invention patents by firms, with coefficients significant at the 10% level. Through the Kleibergen–Paap rk Wald F statistic and Kleibergen–Paap rk LM statistic, it can be seen that there are no under-identification, weak identification and over-identification problems in the instrumental variables. Therefore, after using the instrumental variable method to control the potential endogenous problems, the regression results of this paper are still robust. Specifically, the Kleibergen–Paap F statistics of 118.906 and 3308.954 far exceed the Stock–Yogo critical value of 16.38 for the 10% maximal IV relative bias, strongly rejecting the null hypothesis of weak instruments.

**Table 3.** Instrumental variable regression—the proportion of land conveyance fee.

|                                            | lg_gz                | lg_gsz             | lg_gfz             |
|--------------------------------------------|----------------------|--------------------|--------------------|
|                                            | (1)                  | (2)                | (3)                |
| First-stage:                               |                      |                    |                    |
| IV (The proportion of land conveyance fee) | 0.013 ***<br>(0.001) |                    |                    |
| Second-stage:                              |                      |                    |                    |
| lg_gz                                      |                      | 0.177 *<br>(0.104) | 0.167 *<br>(0.087) |
| KP LM-statistics                           |                      | 117.878            | 117.878            |
| KP F-statistics                            |                      | 118.906            | 118.906            |
| Control variables                          | YES                  | YES                | YES                |
| Firm FE                                    | YES                  | YES                | YES                |
| Year FE                                    | YES                  | YES                | YES                |
| Observations                               | 17,354               | 17,354             | 17,354             |
| R-squared                                  | 0.481                | 0.002              | 0.005              |

Note: \* and \*\*\* indicate significance at the 10% and 1% levels, respectively.

To further alleviate potential endogeneity concerns, this study employs the fiscal self-sufficiency rate as an instrumental variable and implements a two-stage least squares (2SLS) estimation, as reported in Table 4.

The choice of fiscal self-sufficiency rate is based on the following considerations. First, in terms of relevance, the fiscal self-sufficiency rate reflects the extent to which local fiscal revenues can cover local fiscal expenditures. A lower fiscal self-sufficiency rate generally indicates greater fiscal pressure and a wider fiscal gap, which gives local governments stronger incentives to rely on debt financing to maintain infrastructure construction and public spending. Therefore, fiscal self-sufficiency rate is closely related to the scale of local government debt. As shown in Table 4, the coefficient of the instrumental variable in the first-stage regression is 0.022, which is significant at the 1% level, indicating that the instrument has strong explanatory power and satisfies the relevance condition.

Second, regarding exogeneity, the fiscal self-sufficiency rate is largely determined by China's institutional fiscal arrangement, the division of fiscal authority and expenditure responsibility between the central and local governments, and regional fiscal endowments. Compared with firms' green innovation decisions, a regional fiscal constraint and is unlikely to be directly affected by individual firms. After controlling for firm characteristics, firm

fixed effects, and year fixed effects, the fiscal self-sufficiency rate can therefore serve as a reasonably exogenous instrument for local government debt. That said, it should also be acknowledged that regions with lower fiscal self-sufficiency may simultaneously face weaker economic development and innovation environments, which could affect firm innovation through other channels. To mitigate this concern, this study includes a set of control variables and fixed effects to reduce omitted variable bias as much as possible.

The second-stage results show that local government debt still has a significantly positive effect on firm-level green technological innovation. Specifically, the estimated coefficients of local government debt on the total number of green patent applications (*lg\_gsz*) and green invention patent applications (*lg\_gfz*) are 0.096 and 0.0711, respectively, both significant at the 1% level. This indicates that even after addressing endogeneity with the instrumental variable approach, local government debt continues to significantly promote firm-level green technological innovation, confirming the robustness of the main findings.

In addition, the weak instrument tests further support the validity of the instrument. The Kleibergen–Paap LM statistic is 2726.515 and the Kleibergen–Paap F statistic is 3308.954, both far above the commonly accepted critical values, suggesting that weak instrument concerns are unlikely. Overall, the IV results based on fiscal self-sufficiency rate further verify that local government debt significantly promotes firm-level green technological innovation, and the core conclusion of this study remains robust.

**Table 4.** Instrumental variable regression—fiscal self-sufficiency rate.

|                                   | <i>lg_gz</i>         | <i>lg_gsz</i>        | <i>lg_gfz</i>         |
|-----------------------------------|----------------------|----------------------|-----------------------|
|                                   | (1)                  | (2)                  | (3)                   |
| First-stage:                      |                      |                      |                       |
| IV (Fiscal self-sufficiency rate) | 0.022 ***<br>(0.000) |                      |                       |
| Second-stage:                     |                      |                      |                       |
| <i>lg_gz</i>                      |                      | 0.096 ***<br>(0.020) | 0.0711 ***<br>(0.017) |
| KP LM-statistics                  |                      | 2726.515             | 2726.515              |
| KP F-statistics                   |                      | 3308.954             | 3308.954              |
| Control variables                 | YES                  | YES                  | YES                   |
| Firm FE                           | YES                  | YES                  | YES                   |
| Year FE                           | YES                  | YES                  | YES                   |
| Observations                      | 21,120               | 21,120               | 21,120                |
| R-squared                         | 0.512                | 0.001                | 0.005                 |

Note: \*\*\* indicate significance at the 1% levels.

#### 4.3. Robustness Test

As alternative indicators of firm-level green technological innovation, we utilize the logarithm of one plus the total number of green patent grants and the logarithm of one plus the total number of green invention patent grants. The regression results of replacing firm-level green technological innovation indicators are displayed in column (1) and column (2) of Table 5. These robustness results demonstrate that even after substituting the dependent variables, the positive effect of local government debt on firm-level green technological innovation remains significant, validating the core conclusions of this paper. Replace the measurement index of local government debt. The effects of local government debt and its investment in infrastructure may be lagged. Therefore, we select local government debt lagged by two periods as the independent variable. The regression results in Columns (3)–(6) of Table 5 reveal that local government debt lagged by two periods continues to play a significant role in promoting firm-level green technological innovation.

**Table 5.** Robustness test replacing dependent and independent variables.

|                   | lg_gps<br>(1)        | lg_gpfs<br>(2)       | lg_gsz<br>(3)      | lg_gfz<br>(4)       | lg_gps<br>(5)      | lg_gpfs<br>(6)       |
|-------------------|----------------------|----------------------|--------------------|---------------------|--------------------|----------------------|
| lg_gz             | 0.050 ***<br>(0.008) | 0.049 ***<br>(0.005) |                    |                     |                    |                      |
| ll_lg_gz          |                      |                      | 0.013 *<br>(0.007) | 0.013 **<br>(0.006) | 0.014 *<br>(0.008) | 0.019 ***<br>(0.005) |
| Control variables | YES                  | YES                  | YES                | YES                 | YES                | YES                  |
| Firm FE           | YES                  | YES                  | YES                | YES                 | YES                | YES                  |
| Year FE           | YES                  | YES                  | YES                | YES                 | YES                | YES                  |
| Observations      | 21,122               | 21,122               | 13,952             | 13,952              | 13,952             | 13,952               |
| R-squared         | 0.038                | 0.030                | 0.005              | 0.004               | 0.034              | 0.023                |

Note: \*, \*\*, and \*\*\* indicate significance at the 10%, 5%, and 1% levels, respectively.

To further ensure the robustness of our baseline findings, we conduct two additional tests. First, since local government debt is measured at the city level and unobserved city-level shocks may induce correlation among firms within the same city, we re-estimate the baseline model by clustering robust standard errors at the city level rather than at the firm level. Second, because green patent counts contain a large mass of zeros, we employ the Poisson pseudo-maximum likelihood (PPML) estimator to address the potential bias arising from log-transforming count data with zero values. The results, reported in Table 6, show that the positive effect of local government debt on firm-level green technological innovation remains statistically significant under both clustering strategies and the PPML specification, confirming that our core conclusions are not driven by the choice of clustering level or by the distributional properties of the dependent variable.

**Table 6.** Regression models with different clustering methods.

|                            | lg_gps<br>City-Level Clustered<br>Robust Standard Errors<br>(1) | lg_gpfs<br>(2)      | gsz<br>PPML Model<br>(3) | gfz<br>(4)           |
|----------------------------|-----------------------------------------------------------------|---------------------|--------------------------|----------------------|
| lg_gz                      | 0.049 **<br>(0.024)                                             | 0.036 **<br>(0.016) | 0.113 **<br>(0.054)      | 0.173 ***<br>(0.063) |
| Control variables          | YES                                                             | YES                 | YES                      | YES                  |
| Firm FE                    | YES                                                             | YES                 | YES                      | YES                  |
| City FE                    | YES                                                             | YES                 | NO                       | NO                   |
| Year FE                    | YES                                                             | YES                 | YES                      | YES                  |
| Observations               | 21,122                                                          | 21,122              | 20,899                   | 20,844               |
| R-squared/Pseudo R-squared | 0.058                                                           | 0.054               | 0.343                    | 0.380                |

Note: \*\* and \*\*\* indicate significance at the 5%, and 1% levels, respectively. Columns (1)–(2) adopt the robust standard error clustered at city level.

Notwithstanding the instrumental variable approach and multiple robustness checks, residual endogeneity may still persist. We discuss this possibility from three perspectives. First, omitted variable bias is unlikely to invalidate our main conclusions. The firm and year fixed effects account for unobserved time-invariant heterogeneity and common temporal shocks, while the city-level controls capture fiscal capacity and industrial structure. Moreover, the instrumental variable is rooted in historical geographic endowments and pre-determined fiscal institutions, which are largely orthogonal to contemporaneous firm-level innovation behavior. Consequently, unobserved confounders that simultaneously drive both local government debt and firms' green innovation are substantially mitigated. Second,

one may argue that innovation-oriented cities could simultaneously attract greater debt financing and generate stronger green innovation, rendering the estimated coefficient upwardly biased. However, this selection concern is largely absorbed by the firm fixed effects, which control for persistent city–firm matching, and by the instrumental variable, which reflects historical land revenue dependence rather than current innovation orientation.

#### 4.4. Mechanism Analysis

We identify three distinct transmission channels through which local government debt may influence firm-level green technological innovation: green bonds as a green financing channel that relaxes external funding constraints, digital infrastructure as an infrastructure and knowledge spillover channel that lowers information costs and facilitates technology diffusion, and firm profitability as an internal financing channel that frees corporate resources for green R&D. The following sections examine each channel in turn, interpreting the statistical patterns as suggestive pathways rather than definitive causal proof.

##### 4.4.1. Mediating Effect of Investing in Green Bonds

We identify the green bond channel as a green financing conduit, through which local government debt may alleviate corporate financing constraints by expanding the supply of green credit. As previously discussed, while China's local government bonds have traditionally focused on conventional infrastructure, the proportion of green bonds has risen sharply in recent years, with a growing share of special-purpose bonds (SPBs) being directed toward green development projects. This strategic reallocation not only broadens the fiscal capacity of local governments but also creates a catalytic financing environment for green transformation. According to the Guiding Opinions on Further Strengthening Financial Support for Green and Low-Carbon Development, local governments are explicitly encouraged to expand the eligibility of SPB financing to cover eco-environmental protection, clean energy, and other green initiatives. By allocating SPBs to these sectors, authorities effectively reduce the cost of capital for sustainable projects while stimulating private-sector engagement through demonstration effects.

The results of through green bond investment are presented in Table 7. This study uses the ChinaBond Green Bond Environmental Benefit Information Database to collect detailed information on bonds aligned with green issued from 2015 to 2021 and to calculate the issuance amounts of these bonds at the city level. We collected data on 4589 bonds aligned with green issuances from a total of 161 cities. Table 7 illustrates the effect of local government debt on green bond investment. We utilize the logarithm of total bonds aligned with green issuances in cities as a proxy for green bond investment. The regression results in column (1) indicate that the regression coefficient of green bond investment is 0.731, which is statistically significant, suggesting that local government debt significantly promotes green bond investment.

Columns (2) through (5) of Table 7 report the impact of green bond issuance on firm-level green technological innovation, as well as the impact of local government debt on firm-level green technological innovation after introducing green bond issuance variables into the benchmark regression model. In columns (2) and (4), the regression coefficients of green bond issuance on the total number of green patent applications and total number of green invention patent applications are 0.037 and 0.038, respectively, and both are statistically significant. This indicates that higher levels of green bond issuance are associated with stronger firm-level green technological innovation capability. Columns (3) and (5) integrate both local government debt and green bond issuance into the regression model. The regression coefficient of local government debt is negative, whereas the regression coefficients of green bond issuance remain significantly positive. This finding is consistent

with a mediating role for green bond investment, although the estimated pathway remains descriptive rather than strictly causal.

The results in Table 7 indicate that green bond issuance mediates the relationship between debt and innovation through a financing conduit. However, this channel gains plausibility when situated within the carbon finance incentive structure in China. Tang et al. developed a multidimensional valuation framework for China Certified Emission Reductions (CCER) that demonstrates how firms translate green finance signals into innovation decisions [71]. Their framework quantifies the CCER value through probabilistic emission distribution models and captures nonlinear carbon price dynamics using Geometric Brownian Motion and LSTM neural networks. This finding suggests that green bond issuance extends beyond merely expanding the volume of financing; it operates within a broader carbon asset pricing ecosystem in which firms internalize environmental externalities as tradable assets. The channel documented in this study may therefore reflect the strategic positioning of firms for anticipated CCER valuation and carbon market participation, rather than pure liquidity provision.

**Table 7.** The mediating effect of investing in green bonds.

|                        | <b>Greenbonds<br/>(1)</b> | <b>lg_gsz<br/>(2)</b> | <b>lg_gsz<br/>(3)</b> | <b>lg_gfz<br/>(4)</b> | <b>lg_gfz<br/>(5)</b> |
|------------------------|---------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| lg_gz                  | 0.731 ***<br>(0.077)      |                       | −0.046 ***<br>(0.012) |                       | −0.023 **<br>(0.010)  |
| greenbonds             |                           | 0.037 ***<br>(0.005)  | 0.045 ***<br>(0.005)  | 0.038 ***<br>(0.004)  | 0.042 ***<br>(0.004)  |
| City control variables | YES                       | YES                   | YES                   | YES                   | YES                   |
| Firm control variables | -                         | YES                   | YES                   | YES                   | YES                   |
| City FE                | YES                       | -                     | -                     | -                     | -                     |
| Firm FE                | -                         | YES                   | YES                   | YES                   | YES                   |
| Year FE                | YES                       | YES                   | YES                   | YES                   | YES                   |
| Observations           | 373                       | 14,848                | 14,293                | 14,848                | 14,293                |
| R-squared              | 0.346                     | 0.010                 | 0.011                 | 0.010                 | 0.010                 |

Note: \*\* and \*\*\* indicate significance at the 5%, and 1% levels, respectively.

Furthermore, we conduct an industry-focused analysis to examine whether green bonds allocated to a specific industry have stimulated green innovation among firms operating in that sector. By using the electricity, heat, gas, and water production and supply industry as a case study, we find that green bonds allocated to this particular industry have, in fact, effectively promoted green innovation among the enterprises in this field (Table 8).

**Table 8.** The effect of green bond investment in electricity, heat, gas and water production and supply.

| <b>Electricity, Heat, Gas and Water Production and Supply Industry</b> |                       |                       |
|------------------------------------------------------------------------|-----------------------|-----------------------|
|                                                                        | <b>lg_gsz<br/>(1)</b> | <b>lg_gfz<br/>(2)</b> |
| Green bonds                                                            | 0.272 *<br>(0.153)    | 0.256 **<br>(0.126)   |
| City control variables                                                 | YES                   | YES                   |
| Firm control variables                                                 | YES                   | YES                   |
| City FE                                                                | YES                   | YES                   |
| Firm FE                                                                | YES                   | YES                   |
| Year FE                                                                | YES                   | YES                   |
| Observations                                                           | 216                   | 216                   |
| R-squared                                                              | 0.151                 | 0.163                 |

Note: \* and \*\* indicate significance at the 10%, 5% levels, respectively.

#### 4.4.2. Mediating Effect of Digital Infrastructure

The results of the mediating role of local government debt through digital infrastructure investment and development are presented in Tables 9 and 10. We treat digital infrastructure as an infrastructure and knowledge spillover channel, capturing the extent to which debt-financed connectivity lowers information costs and facilitates green technology diffusion.

**Table 9.** The mediating effect of level of digital infrastructure development (Long-distance optical cable density).

|                        | Cable<br>(1)        | lg_gsz<br>(2)        | lg_gsz<br>(3)        | lg_gfz<br>(4)      | lg_gfz<br>(5)        |
|------------------------|---------------------|----------------------|----------------------|--------------------|----------------------|
| lg_gz                  | 0.003 **<br>(0.001) |                      | 0.009<br>(0.008)     |                    | 0.023 ***<br>(0.007) |
| cable                  |                     | 0.265 ***<br>(0.094) | 0.295 ***<br>(0.098) | 0.132 *<br>(0.079) | 0.200 **<br>(0.079)  |
| City control variables | YES                 | YES                  | YES                  | YES                | YES                  |
| Firm control variables | -                   | YES                  | YES                  | YES                | YES                  |
| City FE                | YES                 | -                    | -                    | -                  | -                    |
| Firm FE                | -                   | YES                  | YES                  | YES                | YES                  |
| Year FE                | YES                 | YES                  | YES                  | YES                | YES                  |
| Observations           | 1709                | 22,281               | 20,915               | 22,281             | 20,915               |
| R-squared              | 0.031               | 0.006                | 0.006                | 0.006              | 0.006                |

Note: \*, \*\*, and \*\*\* indicate significance at the 10%, 5%, and 1% levels, respectively.

**Table 10.** The mediating effect of level of digital infrastructure development (Internet penetration rate).

|                        | Internet<br>(1)      | lg_gsz<br>(2)        | lg_gsz<br>(3)        | lg_gfz<br>(4)        | lg_gfz<br>(5)        |
|------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| lg_gz                  | 0.011 ***<br>(0.001) |                      | 0.015 *<br>(0.008)   |                      | 0.027 ***<br>(0.007) |
| Internet               |                      | 0.451 ***<br>(0.084) | 0.530 ***<br>(0.089) | 0.258 ***<br>(0.071) | 0.358 ***<br>(0.075) |
| City control variables | YES                  | YES                  | YES                  | YES                  | YES                  |
| Firm control variables | -                    | YES                  | YES                  | YES                  | YES                  |
| City FE                | YES                  | -                    | -                    | -                    | -                    |
| Firm FE                | -                    | YES                  | YES                  | YES                  | YES                  |
| Year FE                | YES                  | YES                  | YES                  | YES                  | YES                  |
| Observations           | 1709                 | 22,281               | 20,915               | 22,281               | 20,915               |
| R-squared              | 0.168                | 0.007                | 0.007                | 0.006                | 0.007                |

Note: \* and \*\*\* indicate significance at the 10% and 1% levels, respectively.

Table 9 presents the effect of local government debt on long-distance optical cable density (the length of long-distance optical cable routes divided by the administrative area's area), which is one of the indicators used to measure the level of digital infrastructure development. The regression results in column (1) show that the coefficient on long-distance optical cable density is 0.003, which is statistically significant, indicating that local government debt significantly promotes digital infrastructure development. Columns (2) through (5) of Table 9 demonstrate the impact of long-distance optical cable density on firm-level green technological innovation, as well as the impact of local government debt on firm-level green technological innovation after incorporating long-distance optical cable density variables into the benchmark regression model. In columns (2) and (4), the regression coefficients of long-distance optical cable density on the total number of green patent applications and total number of green invention patent applications are

0.265 and 0.132, respectively, and both are statistically significant. This suggests that higher levels of long-distance optical cable density are associated with stronger green technological innovation firm-level green technological innovation capability. Columns (3) and (5) integrate both local government debt and long-distance optical cable density into the regression model. The regression coefficient of long-distance optical cable density remains significantly positive, consistent with a potential mediating role for digital infrastructure development. This indicates that local government debt promotes the green technological innovation of firms by developing digital infrastructure.

Table 10 presents the effect of local government debt on the Internet penetration rate (number of Internet broadband access users divided by the total population), which is also an indicator used to measure the level of digital infrastructure development. The regression results in column (1) indicate that the coefficient on the Internet penetration rate is 0.011, which is statistically significant, suggesting that local government debt significantly promotes digital infrastructure development. Columns (2) through (5) of Table 10 present the impact of the Internet penetration rate on firm-level green technological innovation, as well as the impact of local government debt on firm-level green technological innovation after incorporating the Internet penetration rate variable into the benchmark regression model. In columns (2) and (4), the regression coefficients of the Internet penetration rate on the total number of green patent applications and total number of green invention patent applications are 0.451 and 0.258, respectively, and both are statistically significant. This indicates that higher Internet penetration rates are associated with stronger green technological innovation firm-level green technological innovation capability. Columns (3) and (5) integrate both local government debt and Internet penetration rate into the regression model. The regression coefficient of the Internet penetration rate remains significantly positive, confirming the mediating effect of digital infrastructure development. Therefore, it can be concluded that local government debt promotes the green technological innovation of firms through investment in and development of digital infrastructure.

#### 4.4.3. Mediating Effect of Firm Profitability

We view firm profitability as an internal financing channel, reflecting the capacity of debt-funded public investment to improve corporate liquidity and thereby release resources for green R&D. The results of the mediating role of local government debt through firm gross revenue are presented in Table 11. In column (1), the regression coefficient of local government debt on firm gross revenue is 0.064, which is statistically significant, indicating that local government debt significantly increases firm gross revenue. In columns (2) and (4), the regression coefficients of firm gross revenue on the total number of green patent applications and total number of green invention patent applications are 0.174 and 0.150, respectively, and both are statistically significant. This suggests that an increase in firm gross revenue significantly promotes firm-level green technological innovation. In columns (3) and (5), when both local government debt and firm gross revenue are included in the regression model simultaneously, the regression coefficient of firm gross revenue remains significantly positive. This is consistent with a potential mediating role of firm gross revenue, suggesting that local government debt may promote green technological innovation in part by improving firm profitability. Overall, these results suggest that debt-funded public investment enhances firm liquidity and relaxes internal financial constraints, thereby releasing resources that can be reallocated toward green R&D activities.

The results in Table 11 support the view that improved firm profitability mediates the relationship between debt and innovation by relaxing internal financing constraints. However, this raises a further question: why do freed resources flow specifically into green R&D rather than other competing uses? A portfolio perspective offers a natural answer.

Agrawal and Waggle show that heterogeneous asset exposures, including digital assets, reshape efficient frontiers in multi-asset portfolios spanning equities, bonds, real estate, and commodities [72]. Their framework suggests that individual investment decisions are best understood as part of a broader asset allocation problem in which risk-adjusted returns determine resource reallocation. Applied to the present context, this means green innovation is not an isolated expenditure decision; it is one competing component of the corporate portfolio. When debt-financed public investment improves corporate profitability, the opportunity cost of green R&D falls because the firm can absorb the associated risk without jeopardizing overall portfolio efficiency. As the carbon market in China matures and green technologies de-risk, green innovation becomes a risk-return efficient component of the corporate portfolio, and the profitability channel strengthens accordingly. This interpretation does not overturn the mediation results; it deepens them by connecting firm-level resource reallocation to broader strategic asset management incentives.

**Table 11.** The mediating effect of firm revenue.

|                   | Revenue<br>(1)       | lg_gsz<br>(2)        | lg_gsz<br>(3)        | lg_gfz<br>(4)        | lg_gfz<br>(5)        |
|-------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| lg_gz             | 0.064 ***<br>(0.011) |                      | 0.004<br>(0.007)     |                      | 0.018 ***<br>(0.006) |
| revenue           |                      | 0.174 ***<br>(0.004) | 0.178 ***<br>(0.004) | 0.150 ***<br>(0.004) | 0.153 ***<br>(0.004) |
| Control variables | YES                  | YES                  | YES                  | YES                  | YES                  |
| Firm FE           | YES                  | YES                  | YES                  | YES                  | YES                  |
| Year FE           | YES                  | YES                  | YES                  | YES                  | YES                  |
| Observations      | 21,121               | 22,517               | 21,121               | 22,517               | 21,121               |
| R-squared         | 0.197                | 0.075                | 0.077                | 0.079                | 0.082                |

Note: \*\*\* indicates significance at the 1% levels.

To compare the relative magnitudes of the three channels, we quantify the indirect effects by multiplying the first-stage and second-stage coefficients reported in Tables 7–10. The green bond channel yields the largest indirect effect ( $0.731 \times 0.037 \approx 0.027$ ), exceeding the total effect (0.016) from the baseline regression. The firm profitability channel ranks second ( $0.064 \times 0.174 \approx 0.011$ ). Digital infrastructure contributes modestly ( $0.011 \times 0.451 \approx 0.005$ ). Thus, green bond financing and profitability improvement are the dominant pathways, whereas digital infrastructure plays a complementary role.

#### 4.5. Heterogeneity

##### 4.5.1. City Heterogeneity

This paper examines the influence of local government debt on firm-level green technological innovation from a productivity perspective. Local government officials often consider the level of local economic development when deciding where to invest local government debt. Consequently, this paper introduces the interaction term between local government debt and per capita GDP ( $\text{lg\_gz} \times \text{lg\_per\_gdp}$ ) to investigate whether the impact of local government debt on firm-level green technological innovation varies across regions with different levels of economic development. The regression results, presented in columns (1) and (2) of Table 12, reveal that in cities with higher per capita GDP, local government debt plays a more pronounced role in fostering green technological innovation among firms. This finding suggests that debt directed toward productive capital formation exerts a stronger effect on firm green technological innovation in more economically developed regions.

A city's industrial structure shapes the development patterns of its firms. Therefore, we incorporate the interaction term between local government debt and the proportion

of the tertiary industry in GDP ( $\lg\_gz \times \text{third\_indu}$ ) to investigate whether the impact of local government debt on firm-level green technological innovation varies across regions with different industrial structures. The regression results, presented in columns (3) and (4) of Table 12, demonstrate that in cities with a higher tertiary industry share, local government debt more strongly promotes firm green technological innovation. This finding suggests that local government debt is more effective at promoting firm green technological innovation in regions with a more developed service sector.

**Table 12.** Heterogeneity based on city characteristics.

|                                     | $\lg\_gsz$<br>(1)    | $\lg\_gfz$<br>(2)    | $\lg\_gsz$<br>(3)    | $\lg\_gfz$<br>(4)    |
|-------------------------------------|----------------------|----------------------|----------------------|----------------------|
| $\lg\_gz \times \lg\_per\_gdp$      | 0.002 ***<br>(0.001) | 0.003 ***<br>(0.001) |                      |                      |
| $\lg\_gz \times \text{third\_indu}$ |                      |                      | 0.030 ***<br>(0.006) | 0.042 ***<br>(0.005) |
| Control variables                   | YES                  | YES                  | YES                  | YES                  |
| Firm FE                             | YES                  | YES                  | YES                  | YES                  |
| Year FE                             | YES                  | YES                  | YES                  | YES                  |
| Observations                        | 20,291               | 20,291               | 21,080               | 21,080               |
| R-squared                           | 0.006                | 0.007                | 0.006                | 0.008                |

Note: \*\*\* indicates significance at the 1% levels.

#### 4.5.2. Firm Heterogeneity

The ownership type of firms may also influence the relationship between local government debt and firm-level green technological innovation. State-owned enterprises (SOEs) are subject to stringent government oversight and bear significant social responsibilities spanning both economic and political dimensions. Unlike private firms, SOEs benefit from implicit government guarantees that ease financing constraints for green R&D investment. Their stronger financial resilience enables them to absorb the financial consequences of innovation failures, fostering a more tolerant attitude toward risk-taking. Classified by the ownership type of the actual controllers, the sample firms are divided into SOEs and private firms. We introduce the interaction term between local government debt and the ownership type of firms ( $\lg\_gz \times \text{SOE}$ ) to examine whether the impact of local government debt on firm-level green technological innovation varies across firms with different ownership type. The regression results, presented in columns (1) and (2) of Table 13, demonstrate that local government debt has a more pronounced promoting effect on the green innovation level of state-owned firms.

Firm size is a critical factor influencing the green innovation capability of firms. Large firms possess advantages such as capital, personnel, and technological reserves, leading to higher green innovation capabilities. However, they also face issues like institutional redundancy, which can result in lower innovation enthusiasm and efficiency. By contrast, small- and medium-sized firms (SMEs) are often constrained by financing limitations. Despite having high innovation willingness and efficiency, SMEs generally face insufficient R&D investment due to difficulties in obtaining financing. Large firms are also better positioned to benefit from debt-financed public investment, which improves the external innovation environment through digital infrastructure and knowledge spillovers, as documented in Section 4.4. We introduce the interaction term between local government debt and the total asset of firms ( $\lg\_gz \times \lg\_as$ ) to examine whether the impact of local government debt on firm-level green technological innovation varies across firms with different sizes. The regression results, presented in columns (3) and (4) of Table 13, demonstrate that local government debt has a more pronounced promoting effect on green technological innovation in

large firms. It can be argued that as the scale of firms increases, the promoting effect of local government debt on the green innovation capability of firms becomes more pronounced.

**Table 13.** Heterogeneity based on firm characteristics.

|                   | lg_gsz<br>(1)        | lg_gfz<br>(2)        | lg_gsz<br>(3)        | lg_gfz<br>(4)        | lg_gsz<br>(5)        | lg_gfz<br>(6)        |
|-------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| lg_gz × SOE       | 0.019 ***<br>(0.002) | 0.020 ***<br>(0.002) |                      |                      |                      |                      |
| lg_gz × lg_as     |                      |                      | 0.005 ***<br>(0.000) | 0.005 ***<br>(0.000) |                      |                      |
| lg_gz × esg       |                      |                      |                      |                      | 0.017 ***<br>(0.001) | 0.015 ***<br>(0.001) |
| Control variables | YES                  | YES                  | YES                  | YES                  | YES                  | YES                  |
| Firm FE           | YES                  | YES                  | YES                  | YES                  | YES                  | YES                  |
| Year FE           | YES                  | YES                  | YES                  | YES                  | YES                  | YES                  |
| Observations      | 20,493               | 20,493               | 21,016               | 21,016               | 21,122               | 21,122               |
| R-squared         | 0.009                | 0.011                | 0.022                | 0.028                | 0.034                | 0.036                |

Note: \*\*\* indicates significance at the 1% levels.

ESG (Environmental, Social, and Governance) performance has also emerged as an important determinant of corporate outcomes. Although neoclassical theory suggests that ESG performance does not enhance corporate operational performance and may even hinder the achievement of maximizing corporate value due to its strong externalities [73], recent studies have found that in environments with asymmetric information, corporate ESG performance helps gain the trust of stakeholders such as financial institutions, suppliers, and customers, thereby reducing operational costs and improving operational efficiency [74]. Additionally, evidence indicates that ESG rating disagreement exerts a disciplining effect on corporate green innovation, as firms respond to rating divergence by intensifying environmental patenting activities to signal genuine commitment [75]. Some scholars also argue that as countries place greater emphasis on environmental and other social issues, ESG advantages enable companies to better overcome hidden barriers in corporate investments, such as safety inspections or environmental protection. However, these studies mostly explore the relationship between ESG performance and daily corporate operations, and there is no clear answer as to whether ESG affects local government debt and corporate green innovation. It is generally believed that the environmental regulatory pressure arising from sustainability demands forces companies to participate in green innovation to change traditional high-polluting and high-energy-consuming production methods. In this process, governments often support corporate green innovation through policies such as fiscal subsidies or tax exemptions. At the same time, the externalities of ESG itself may also lead to inefficiencies in innovation investment. Taking into account the applicability period and coverage of various ESG ratings, we use the Huazheng ESG rating as a proxy variable for corporate ESG performance. The Huazheng Index has been assessing the ESG performance of A-share and bond issuers since 2009, covering all A-share listed companies. The index has been widely recognized by industry and academia. We introduce the interaction term between local government debt and the ESG rating of firms (lg\_gzeg) to examine whether the impact of local government debt on firm-level green technological innovation varies across firms with different ESG rating. The regression results, presented in columns (5) and (6) of Table 13, demonstrate that local government debt has a more pronounced promoting effect on green technological innovation in firms with high ESG ratings.

#### 4.6. Further Analysis

China's local government implicit debt—off-balance-sheet liabilities incurred primarily through Local Government Financing Vehicles (LGFVs) that local governments do not fully disclose—poses significant risks to financial stability and economic development. Despite regulatory efforts, many local governments continue to accumulate LGFV debt to fund infrastructure projects, and the resulting opacity makes it difficult to assess the true scale of obligations. Furthermore, implicit debt frequently finances projects with uncertain returns, creating a mismatch between debt servicing capacity and project profitability that elevates default risk for both local governments and their creditors.

Moreover, the interconnectedness of financial institutions with local governments and their LGFV platforms creates contagion risk: a default in one sector can rapidly spread across the financial system, undermining investor confidence and triggering market volatility. Implicit debt also distorts fiscal incentives by exacerbating moral hazard: the expectation of central government bailouts encourages continued LGFV borrowing, perpetuating financial fragility. To assess the impact of implicit debt on green technological innovation in firms, we use the LGFVs debt balance (logarithm) as a proxy variable for implicit debt and conduct regression analysis. The regression results regarding the effects of implicit debt on the green technological innovation of firms are presented in Table 14. Columns (1)–(4) depict the outcomes of the impact on the total number of green patent applications, total number of green invention patent applications, total number of green patent grants, and total number of green invention patent grants. All regressions incorporate firm fixed effects and year fixed effects. From the regression results, it is observed that the impact of changes in implicit debt on the total number of green patent applications is negatively significant at the 10% level, indicating that implicit debt to some extent impedes green technological innovation in firms. The impact of implicit debt on the total number of green invention patent applications, total number of green patent grants, and total number of green invention patent grants is negative but not significant.

**Table 14.** The effect of implicit debt on green technological innovation of firms.

|                   | lg_gsz<br>(1)       | lg_gfz<br>(2)     | lg_gps<br>(3)     | lg_gpfs<br>(4)   |
|-------------------|---------------------|-------------------|-------------------|------------------|
| lg_fv             | −0.011 *<br>(0.007) | −0.002<br>(0.006) | −0.002<br>(0.007) | 0.004<br>(0.005) |
| Control variables | YES                 | YES               | YES               | YES              |
| Firm FE           | YES                 | YES               | YES               | YES              |
| Year FE           | YES                 | YES               | YES               | YES              |
| Observations      | 21,671              | 21,671            | 21,671            | 21,671           |
| R-squared         | 0.010               | 0.010             | 0.041             | 0.033            |

Note: \* indicates significance at the 10% levels.

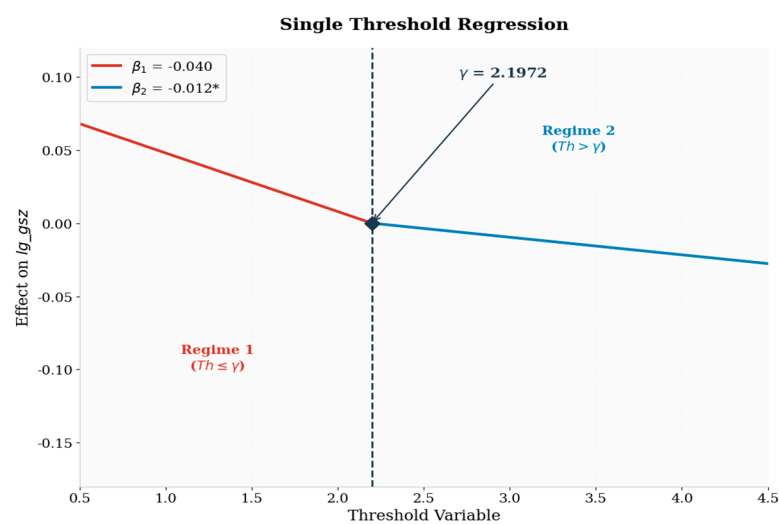
The relationship between implicit debt and firm green technological innovation may be nonlinear. We test this using a panel threshold regression model. Before estimation, we examined the existence of thresholds based on the Hansen [76] method. We employ the Bootstrap method with 400 resampling iterations. The results indicate that in the test where the total number of green patent applications serves as the dependent variable, the threshold variable of implicit debt balance significantly passes the single threshold test but fails the double threshold test. Consequently, we established a single threshold regression model based on this finding, presenting the results in Table 15. Figure 5 offers a graphical illustration of this single-threshold effect, depicting the distinct regimes of implicit debt's impact on firm-level green technological innovation. As implicit debt increases, its effect on firm-level green technological innovation undergoes significant

changes. Implicit debt demonstrates a nonlinear pattern of influence on green technological innovation, initially showing insignificance and then presenting a noteworthy limitation. Specifically, when the threshold variable of implicit debt balance (log) is below 2.1972, the coefficient of implicit debt is  $-0.040$  and its impact is insignificant, suggesting that moderate implicit debt is permissible and does not materially suppress green innovation, provided borrowing is strictly monitored and directed toward productive investment. However, when the threshold variable exceeds 2.1972, the coefficient becomes  $-0.012$  and significant at the 10% level, indicating that excessive LGFV borrowing significantly hampers firm-level green technological innovation through inefficient investments, heightened financing constraints, and increased financial risks. Given that the sample mean of log implicit debt (6.496) far exceeds this threshold, the inhibitory regime applies to the vast majority of cities in our sample. This implies that widespread de-risking and deleveraging of LGFVs should be prioritized, with financing gradually shifted toward explicit bonds and green bond instruments to restore corporate innovation incentives and sustainable economic development.

**Table 15.** The nonlinear effect of implicit debt on green technological innovation of firms.

|                      |    | lg_gsz                |
|----------------------|----|-----------------------|
| Threshold variable   | q1 | 2.1972                |
| lg_fv (Th $\leq$ q1) |    | $-0.040$<br>(0.064)   |
| lg_fv (Th $>$ q1)    |    | $-0.012^*$<br>(0.007) |
| Control variables    |    | YES                   |
| Firm FE              |    | YES                   |
| Year FE              |    | YES                   |
| Observations         |    | 21,671                |
| R-squared            |    | 0.033                 |

Note: \* indicates significance at the 10% levels.



**Figure 5.** Single Threshold Regression (\* indicates significance at the 10% levels).

## 5. Conclusions and Discussion

### 5.1. Conclusions

Focusing on the 2015–2021 period, during which the local government debt governance framework in China was continuously improved, this study examines the impact of local government debt on firm-level green technological innovation from the perspective of

debt productivity, using city-level debt data matched with firm-level data from Chinese A-share listed companies. The main conclusions are as follows: First, explicit local government debt (general and special bonds) under the standardized governance framework significantly promotes firm-level green technological innovation, indicating that when debt funds are oriented toward productive public investment, local government debt can serve as an effective policy instrument to drive green innovation. Second, mechanism analysis reveals that local government debt fosters green innovation through three channels: green bond investment, digital infrastructure development, and firm profitability enhancement. These channels operate by alleviating financing constraints, improving the regional innovation environment, and strengthening firms' internal resource capacity for R&D. Third, heterogeneity analysis shows that the promoting effect is more pronounced in economically developed regions and those with a more developed service sector, and among state-owned, large-sized, and high-ESG-rated firms. These findings highlight the moderating role of regional institutional quality and firm-level resource endowment. Fourth, implicit debt (LGFVs) exerts a nonlinear effect on firm green technological innovation. When the implicit debt balance remains below the threshold (log value of 2.1972), its effect is statistically insignificant; once the threshold is exceeded, it significantly impedes green innovation. This underscores the need for sustained implicit debt governance and proactive risk monitoring.

## 5.2. Discussion

### 5.2.1. Theoretical Contributions

Our findings both complement and challenge the existing literature. Chen et al. [28] documented that rising local government debt exacerbates financing constraints and suppresses firm green technological innovation in China. We attribute this divergence to institutional context and debt structure. Chen et al. likely captured the pre-reform period, when implicit debt expansion dominated, whereas our sample (2015–2021) covers the post-reform era when explicit debt became the primary financing tool [28]. The 2014 reform introduced hard budget constraints and directed debt proceeds toward productive public investment rather than recurrent expenditure, thereby mitigating the crowding-out effect identified by Fan et al. [33] and Huang et al. [51]. Our results also align with Kantorowicz et al. [24], who argue that debt financing for green investment encounters less public opposition than taxation. Whereas they focus on macro-level public acceptance, we provide micro-level evidence that debt-funded green bonds and digital infrastructure translate fiscal capacity into corporate innovation outcomes, bridging the macro-fiscal and micro-innovation literature. The nonlinear effect of implicit debt resonates with Brixi's [29] fiscal risk matrix and the debt sustainability literature [8,9]. Our threshold regression confirms that implicit debt is not inherently detrimental below a certain scale, but excessive off-balance-sheet borrowing distorts fiscal incentives and squeezes corporate credit, consistent with the systemic risk arguments of Wang et al. [32] and Fan et al. [33]. Unlike Zhou et al. [20], who focused on the pollution consequences of urban investment bonds, we reveal the innovation dimension of implicit debt externalities, demonstrating that debt structure shapes not only environmental quality but also long-term technological capacity.

This study advances the literature along four dimensions. First, it enriches the literature on economic consequences of government debt by shifting the focus from macro growth debates to micro-level green innovation outcomes. Prior studies have extensively examined whether government debt promotes or inhibits economic growth [5,6,8]; however, few have explored its implications for green economic transition. By distinguishing explicit from implicit debt and identifying their differential effects, we offer a nuanced understanding of how debt structure shapes environmental performance at the firm level. Second, we contribute to the green innovation literature by identifying local government

debt as a novel institutional driver. While existing research emphasizes environmental regulation, green finance development, and government subsidies [14,15,18], our study reveals that debt governance reform creates an exogenous policy shock that reshapes innovation incentives. The mediation analysis suggests that green bonds and digital infrastructure serve as critical transmission mechanisms, bridging the resource-based view with institutional theory in innovation studies. Third, our theoretical model integrates fiscal policy, firm innovation decisions, and environmental externalities into a unified framework. Unlike prior studies that treat public investment and private innovation separately, our model captures the spillover effects of green bond issuance and digital infrastructure on firm-level green technology accumulation. This provides a formal foundation for understanding productive government spending in environmental economics. Fourth, we extend the digital infrastructure literature by examining its ecological implications. Previous studies predominantly assessed the economic impacts of traditional infrastructure [46–49] or the growth effects of digital infrastructure [30], while largely neglecting its environmental implications. Our findings demonstrate that digital infrastructure investment significantly mediates the debt–innovation nexus, suggesting that the “new infrastructure” strategy can serve as a dual-purpose tool for economic digitalization and ecological modernization.

### 5.2.2. Implications

These findings carry direct policy implications. Local governments should optimize the allocation of explicit debt by establishing rigorous project screening criteria that prioritize green transformation and digital upgrading. Special-purpose bonds should be directed toward projects with clear revenue streams and demonstrable environmental benefits, such as renewable energy infrastructure, smart grids, green transportation systems, and low-carbon industrial parks. General debt, meanwhile, should be reserved for public welfare projects that enhance human capital and innovation capacity, including research platforms, technology incubators, and environmental monitoring networks. Ex-ante feasibility studies and ex-post performance audits can ensure that each unit of debt generates measurable green innovation outcomes rather than merely expanding government balance sheets.

Regarding implicit debt, regulators should strengthen oversight of LGFVs and other off-balance-sheet entities by integrating their liabilities into a unified national monitoring platform. Mandatory disclosure of contingent liabilities, coupled with real-time tracking of debt service coverage ratios and project-level cash flows, would help prevent the accumulation of hidden risks. Local governments should accelerate the market-oriented transformation of LGFVs, severing implicit government guarantees and hardening budget constraints to mitigate moral hazard. A quantitative risk assessment framework incorporating early warning thresholds for debt-to-revenue ratios and interest burden rates is essential for preemptive intervention before distress materializes.

To scale up green bond financing, policymakers should harmonize domestic green bond standards with international frameworks such as the ICMA Green Bond Principles and the EU Taxonomy, reducing certification costs and attracting cross-border capital. Tax incentives for green bond investors and interest subsidies for municipal issuers can lower financing costs and stimulate supply. Furthermore, expanding the eligible use of special-purpose bonds to include green projects, and allowing proceeds to cover operation and maintenance costs during the initial ramp-up phase, would enhance project viability and bankability. Local governments should also mandate independent third-party verification and annual post-issuance impact reporting to safeguard market credibility and deter greenwashing.

Strategic investment in digital infrastructure requires moving beyond generic connectivity targets toward sector-specific applications that directly enable green innovation. Local

governments should prioritize 5G networks, industrial internet platforms, smart energy management systems, and urban data centers that facilitate real-time emissions monitoring, resource optimization, and circular economy practices. Integrating digital infrastructure with traditional sectors, such as intelligent agriculture and smart manufacturing, can create productivity gains that justify debt financing and generate fiscal returns. Public and private partnership models should be designed to share both investment burdens and data assets, ensuring that digital public goods remain accessible to small- and medium-sized enterprises rather than being captured by large state-owned entities.

Balancing innovation promotion with long-term debt sustainability requires a dynamic debt management framework. Policymakers should adopt performance-linked debt ceilings where verified green innovation outputs—measured by patent quality or emissions reductions—serve as a qualifying condition for new issuance, rather than relying solely on rigid GDP-based ratios. Project-level debt service coverage requirements and life-cycle cost–benefit analyses should be strictly enforced to prevent the approval of economically unviable projects. Additionally, stabilization funds financed by land conveyance revenues, carbon trading proceeds, and environmental taxes can buffer debt repayment pressures during economic downturns without forcing abrupt cuts to innovation spending.

These policy insights are relevant beyond China to other emerging economies facing challenges of fiscal decentralization and green transition financing. In countries such as Brazil, India, and South Africa, where subnational governments face structural mismatches between expenditure responsibilities and revenue authority, formalizing local government bond markets rather than relying on opaque financing vehicles can channel capital more efficiently toward sustainable development. Emerging economies should consider designing green fiscal rules that exempt productive environmental investment from rigid deficit caps, thereby encouraging innovation-friendly debt accumulation. International financial institutions, including the World Bank and regional development banks, could support this agenda by providing technical assistance for green bond market development, standardized implicit debt disclosure frameworks, and credit enhancement facilities tailored to emerging-market contexts.

### *5.3. Limitations and Future Research*

This study faces several constraints worth noting. Our sample period ends in 2021, reflecting the institutional reality that special bonds were first issued in 2015, and we deliberately exclude 2022 and 2023 to avoid confounding effects from the COVID-19 pandemic, the real estate downturn, and intensive local debt resolution policies. The analysis also focuses exclusively on Chinese A-share listed firms, whose innovation behavior and financing channels may differ substantially from unlisted firms, SMEs, or subsidiaries of listed companies. Although the instrumental variable approach mitigates endogeneity concerns, residual endogeneity cannot be entirely ruled out. Local governments with stronger innovation orientations may simultaneously expand debt financing and promote corporate green innovation through targeted industrial policies or R&D subsidies, and our instrument, land conveyance revenue dependence, may not fully isolate such common-cause dynamics. We therefore interpret our findings as compelling evidence rather than definitive causal proof. The mediation analysis is best viewed as suggestive evidence of potential transmission channels. The estimated indirect effects illuminate plausible mechanisms but should not be interpreted as establishing strict causal pathways, given that the mediator variables are themselves endogenous outcomes. A related limitation is that the green bond measure employed in this study captures issuance quantity rather than market quality. The estimated coefficients are statistically significant across specifications, suggesting that the volume channel is operative; however, this quantity-based proxy may not fully reflect

the cost of capital that firms face in practice. Shahrour et al. [77] show that label-based or quantity-based metrics of green finance instruments can diverge significantly from efficiency-adjusted assessments, as green labels alone do not guarantee optimal risk-return outcomes. This concern is relevant here: issuance volume may overstate the effective green financing available to firms if the underlying bonds carry high illiquidity premiums or lack secondary market depth. Agrawal and Clark further note that bond liquidity resists single-metric proxies; their multidimensional A-C score incorporates bid–ask spreads, market capitalization, and trading volume, revealing that liquidity persistence evolves over time [78]. Taken together, these studies imply that the measure employed in this study captures the extensive margin of green finance but may miss the intensive margin of market efficiency, and that future research could integrate market microstructure data to examine whether the channel operates through volume expansion, yield compression, or genuine liquidity improvement. Finally, the measurement of digital infrastructure warrants careful interpretation. While long-distance optical cable density and internet penetration rate provide relatively precise proxies for digital connectivity, the use of aggregate fixed asset investment as a proxy is subject to substantial imprecision, as it encompasses non-digital components such as real estate, transportation, and traditional construction. Additionally, while the theoretical model in Section 2.4 integrates fiscal policy, firm innovation, and environmental externalities into a unified framework, the empirical estimation remains reduced-form and does not recover deep structural parameters. We therefore interpret the model as a motivational device guiding hypothesis development rather than as a validated structural representation of the data-generating process.

Future research could address these limitations in several directions. Scholars could examine how recent debt resolution shocks affect corporate green innovation rather than simply extending the sample period, and expand the analysis to SMEs and unlisted enterprises to provide a comprehensive understanding of how local government debt shapes green innovation across the entire corporate landscape. It is recommended that future work exploit quasi-experimental designs, such as exogenous central government debt quota allocations or discrete policy shocks, to achieve sharper causal identification.

For the green bond channel, researchers should move beyond quantity-based measures by integrating efficiency-adjusted valuation frameworks such as those developed by Shahrour et al. [77] for ESG assets and by Tang et al. [71] for CCER pricing. The integration of market microstructure data and multidimensional liquidity scoring along the lines of Agrawal and Clark [78] is encouraged to clarify whether the channel operates through volume expansion, yield compression, or genuine liquidity improvement, as these mechanisms carry distinct implications for corporate innovation incentives. Researchers should also employ more refined indicators such as information technology investment or new infrastructure expenditure to enhance measurement precision for digital infrastructure.

Beyond these extensions, other potential mechanisms, including human capital accumulation, environmental regulation stringency, and industrial policy alignment, remain unexplored and warrant further investigation. Comparative studies across countries with different fiscal federalism structures could additionally assess the generalizability of our findings beyond the Chinese context. Finally, reconceptualizing the profitability channel as a portfolio reallocation problem, following Agrawal and Waggle [72], would place firm-level green investment decisions within a richer theory of strategic asset management.

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## Appendix A. Theoretical Derivations

### Appendix A.1. Firm Intertemporal Optimization

Firms maximize their present value of profits:

$$\max_{\{K_{it}, L_{it}, I_{it}^{green}\}} \sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} \left[ Y_{it} - w_t L_{it} - r_t K_{it} - C(I_{it}^{green}, \mathcal{E}_{i,t-1}) \right]$$

subject to the green technology accumulation equation, where  $\rho$  is the discount rate and  $C(\cdot)$  represents the cost function of green innovation, which is convex in investment and decreasing in existing green technology stock.

### Appendix A.2. Government Social Welfare Maximization

The local government maximizes social welfare:

$$\max_{\{D_t^{exp}, D_t^{imp}, GB_t, DI_t\}} \sum_{t=0}^{\infty} \beta^t \left[ U(C_t^h) + \lambda \cdot \sum_i \mathcal{E}_{it} - \Omega(D_t^{imp}) \right]$$

subject to the budget constraint, where  $C_t^h$  is household consumption,  $\lambda$  represents the social valuation of environmental quality, and  $\Omega(\cdot)$  denotes the risk cost of implicit debt, which is increasing and convex:  $\Omega'(D^{imp}) > 0$ ,  $\Omega''(D^{imp}) > 0$ .

### Appendix A.3. First-Order Condition and Implicit Debt Threshold

From the firm’s first-order condition with respect to green R&D:

$$\frac{\partial \mathcal{E}_{it}}{\partial I_{it}^{green}} = \frac{1}{\phi} \cdot \Psi_{ct} \cdot \mathcal{E}_{i,t-1} \cdot \left( \beta \cdot \frac{\partial Y_{it}}{\partial \mathcal{E}_{it}} + \frac{\partial C_{t+1}}{\partial \mathcal{E}_{it}} \right)$$

Since  $\frac{\partial \Psi_{ct}}{\partial D_{ct}^{exp}} = \psi_1 > 0$  and  $\frac{\partial GB_t}{\partial D_{ct}^{exp}} > 0$ ,  $\frac{\partial DI_t}{\partial D_{ct}^{exp}} > 0$ , we have  $\frac{\partial \mathcal{E}_{it}}{\partial D_{ct}^{exp}} > 0$ .

The financing environment index  $\Psi_{ct}$  remains constant at  $\Psi_0$  for  $D_{ct}^{imp} \leq \bar{D}$ , but decreases quadratically when the threshold is exceeded:

$$\frac{\partial \Psi_{ct}}{\partial D_{ct}^{imp}} = \begin{cases} 0 & \text{if } D_{ct}^{imp} \leq \bar{D} \\ -2\psi_2(D_{ct}^{imp} - \bar{D}) < 0 & \text{if } D_{ct}^{imp} > \bar{D} \end{cases}$$

This creates a kinked relationship between implicit debt and green innovation.

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