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Financing the Twin Transition: How Patent Pledges Leverage Intangible Assets for Digital–Green Synergistic Transformation

An Pan[1] | Puyu Mi[2] | Yijiao Shi[3] | Xunpeng Shi[4]

[1]School of Business, Shaoxing University, Zhejiang, China | [2]School of Economics and Trade, Zhongnan University of Economics and Law, Wuhan, Hubei, China | [3]School of Economics, Fudan University, Shanghai, China | [4]Australia-China Relations Institute, University of Technology Sydney, Sydney, New South Wales, Australia

Correspondence: Xunpeng Shi (xunpeng.shi@uts.edu.au)

Received: 24 March 2026 | **Revised:** 28 July 2026 | **Accepted:** 4 September 2026

Keywords: digital–green synergistic transformation | financing constraints | innovation structure | managerial incentives | patent pledge

ABSTRACT

Against the backdrop of aligning digital expansion with green growth objectives, exploring effective financial support pathways for firms' digital–green synergistic transformation (DGST) holds significant theoretical and practical value. This study examines the impact, mechanisms, and heterogeneity of patent pledge financing on firms' DGST, using data from Chinese A-share listed companies between 2010 and 2022. The results show: First, patent pledges significantly promote DGST, and this finding remains robust after robustness checks and endogeneity treatments. Second, mechanism analysis confirms that alleviating financing constraints and optimizing innovation structure are the key channels through which patent pledges drive DGST; by addressing funding bottlenecks and improving the allocation of innovation resources, they provide dual support for integrated digital–green development. In addition, patent pledges enhance managerial incentives, further promoting DGST. Third, we uncover significant regional and corporate divergence in how patent pledges drive DGST. The impact intensifies for high-tech entities and those with robust banking ties and large-scale firms, whereas regional factors such as heightened green commitment and digital maturity further amplify these benefits. Fourth, debt default risk weakens the positive effect of patent pledges on DGST. Moreover, both digital patent pledges and green patent pledges significantly promote DGST, whereas only invention patent pledges exhibit a significant transformation effect, highlighting the importance of patent quality and financing capacity. This study enriches the literature on intellectual property finance and DGST, offering empirical evidence and policy implications for improving patent pledge financing systems and promoting high-quality corporate transformation.

1 | Introduction

The paradigm of the digital–green synergistic transformation (DGST) now functions as a primary catalyst for elevating corporate performance standards and aligning firm-level operations with contemporary environmental imperatives. Catalyzed by the ongoing intensification of global climate governance and the rapid proliferation of the digital economy. It also serves as a critical lever for upgrading the real economy toward a low-carbon, efficient, and intelligent model. DGST refers to the synergistic transformation of firms' digitalization and greening processes. Rather than a simple aggregation of digital and green initiatives, DGST embodies an interactive and mutually reinforcing evolutionary process characterized by interdependence and complementarity. This process fosters a pattern of integrated "symbiosis" and generates dual improvements in innovation efficiency and environmental performance through "bidirectional empowerment" (Li et al. 2022; Alabdali et al. 2024).

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Digital transformation enhances production efficiency and optimizes value chain coordination, thereby providing technological support and data infrastructure for green transformation. In turn, green transformation establishes low-carbon orientations and resource constraints that guide digital development. Collectively, these processes underpin an emerging framework for corporate manufacturing advancement and the generation of economic value (Wang and Dong 2024). Empirical evidence suggests that DGST not only facilitates the cultivation of new quality productive forces (Shan et al. 2025) but also promotes breakthroughs in key core technologies (Zheng et al. 2025). Moreover, by alleviating the negative effects of resource misallocation, it fosters more environmentally oriented innovation practices (Ye et al. 2024). As such, DGST has become an important strategic choice for firms seeking sustainable development amid market competition and regulatory pressures.

However, the advancement of DGST faces pronounced financing constraints, a challenge that is particularly salient for innovative firms (Hall 2002). DGST embodies both the technology-intensive nature of digital innovation and the capital-intensive characteristics of green transformation. Its implementation requires substantial R&D expenditures, continuous upgrading of equipment, and trial-and-error experimentation in business model innovation. These ventures entail prolonged investment cycles, substantial uncertainty, and acute asset specialization (Martínez-Ros and Kunapatarawong 2019; Noailly and Smeets 2022). Conventional credit mechanisms are often constrained by informational friction, where the dual challenges of adverse selection and moral hazard compel lenders to prioritize tangible asset backing (Stiglitz and Weiss 1981). By contrast, the core assets of innovative firms are typically intangible assets such as patents and proprietary technologies. These assets are difficult to value and have limited liquidity, making them unsuitable as effective collateral in conventional lending arrangements (He and Tian 2018; Zhang et al. 2021). Conventional bank lending relies heavily on tangible collateral such as fixed assets. Within China's financial system, where corporate financing relies heavily on bank lending (Allen et al. 2005), the collateralization dilemma of intangible assets constitutes a significant barrier constraining firms' investment and innovation activities related to DGST. How to alleviate such financing constraints and provide sustained financial support for firms' DGST has therefore become a central concern for both academia and practice.

Patent pledge financing offers a financial instrument capable of supporting high-quality transformation in knowledge-intensive enterprises. Patent pledge financing breaks through this traditional debt financing framework by using patent rights—an intangible asset—as the core collateral. It directly transforms a firm's technological value and innovative capability into pledgeable credit, enabling intellectual property to function as a financial asset (Fischer and Ringler 2014). By incorporating firms' technological knowledge, innovative outputs, and future growth potential into lending contracts, patent pledges expand the boundary of acceptable collateral beyond tangible assets (Hochberg et al. 2018). In doing so, this intellectual property–based financing model responds to a structural mismatch in which innovative firms possess a high proportion of intangible assets, yet traditional collateralized lending primarily recognizes fixed assets (Stiglitz and Weiss 1981). With innovation value serving as the foundation of creditworthiness, technological growth as implicit repayment security, and transformation and upgrading as the primary investment direction, patent pledge financing constitutes a novel financial instrument better aligned with firms pursuing DGST than conventional financing. As an innovative financing model in which firms obtain bank loans by pledging legally owned patent rights, patent pledge financing has become an important mechanism for activating intangible assets and alleviating financing pressures faced by innovative enterprises (Fischer and Ringler 2014; Hochberg et al. 2018). Against this backdrop, whether patent pledge financing can promote firms' DGST is a critical question concerning their ability to overcome financing constraints and achieve sustainable innovation-driven development.

Nonetheless, the existing literature remains limited in several critical respects. Much of the prior research emphasizes regional- or industry-level analyses at the macro level, leaving quantitative examinations of firm-level drivers and the underlying mechanisms of DGST comparatively underexplored. In particular, there is a distinct absence of systematic investigation into how intellectual property–based financing instruments, such as patent pledge financing, affect DGST.

To address this issue, this study employs a sample of Chinese A-share listed firms over the period 2010–2022 to systematically examine the impact, underlying mechanisms, and heterogeneity of patent pledge financing on firms' DGST. Since the promulgation of the Administrative Measures for the Registration of Patent Pledge Contracts in China in 1996, patent pledge financing has developed rapidly under sustained policy support. It has evolved from a purely market-based transaction into a strategic national initiative aimed at serving enterprise innovation, thereby becoming an important bridge linking intellectual property value with real economic development. As a major arena for digital economy development and green transformation worldwide, China has witnessed the continuous expansion of the scale and coverage of patent pledge financing, providing a unique institutional context and rich empirical setting for examining patent pledges.

The marginal contributions of this study are as follows. First, by utilizing detailed data on actual firm-level patent pledge activities, this study investigates their comprehensive impact mechanism on firms' DGST. However, existing studies on patent pledge financing in China primarily focus on city-level patent pledge policies (Xie et al. 2023; Li, Zhang, et al. 2024; Gong et al. 2024; Shi et al. 2025), making it difficult to accurately capture firm-level patent pledge practices. Second, by examining how patent pledge financing drives corporate DGST, this study transcends current scholarly silos that treat innovation and environmental objectives as mutually exclusive domains. The extant literature largely concentrates on the singular effects of patent pledge financing on corporate innovation (Mann 2018; De Rassenfosse and Palangkaraya 2023; Li, Zhang, et al. 2024) or green development (Gong et al. 2024; Shi et al. 2025). Although existing literature addresses how financing constraints affect digital (Luo 2021) and green transitions (Ren et al. 2025), it has not explored how patent pledge financing influences the DGST. Third, we uncover significant heterogeneity in the impact of patent pledges on DGST. The benefits are most pronounced for

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high-tech entities, firms with robust banking ties, and those situated in regions characterized by strong green commitment and advanced digital infrastructure. Furthermore, we extend the heterogeneity analysis to pledged patent characteristics, showing that digital and green patent pledges both promote DGST, whereas only invention patent pledges have a significant effect. This provides a more nuanced understanding of how patent quality and technological attributes shape the effectiveness of patent pledge financing. Our analysis yields empirical support and strategic guidance at the firm level for formulating differentiated intellectual property–based financial support policies and enhancing the effectiveness of DGST-related initiatives.

The subsequent sections are structured as follows. In Section 2, we review the literature and develop the hypotheses, including the underlying mechanisms. Section 3 provides the details of the data and the econometric methodology employed. Section 4 reports the empirical results and discussion. Section 5 summarizes the conclusions and provides recommendations for policy intervention.

2 | Literature Review and Research Hypothesis

2.1 | Literature Review

Existing research has conducted extensive discussions on digital transformation, green transformation, and their synergistic development. In the field of digital transformation, scholars generally contend that digital transformation not only drives fundamental changes in corporate business strategies and thereby enhances value creation (Feliciano-Cestero et al. 2023) but is also closely associated with corporate sustainability, providing critical support for sustainable development (Pan et al. 2022). Meanwhile, the advancement of the digital revolution and the proliferation of digital platforms have broken down traditional boundaries of firm development, creating substantial opportunities for entrepreneurial innovation and business expansion (Nambisan et al. 2019; Bouncken and Barwinski 2021), further underscoring the central role of digital transformation in corporate growth. However, corporate digitalization is invariably plagued by prominent financing challenges that hinder its in-depth advancement. Digital transformation entails substantial upfront investments in technological infrastructure and iterative R&D in the early stage, and many enterprises are constrained by insufficient capital reserves to sustain such long-term and high-risk investment demands (Luo 2021). Moreover, digital innovation projects are often accompanied by high information opacity as enterprises tend to keep core project information confidential to protect trade secrets, thereby intensifying informational friction and dampening institutional appetite for digital-centric financing (Wan et al. 2020). In this context, the availability of external financing and the efficiency of capital allocation have become key factors restricting the smooth progress of corporate digitalization, making it imperative to explore targeted financial support mechanisms to address these financing bottlenecks.

In the domain of green transformation, the literature has primarily focused on identifying its driving forces, generating a rich body of findings. Studies show that various external factors and policy instruments can effectively promote green transformation at both the firm and industry levels. For instance, digital finance can facilitate industrial green transformation by optimizing resource allocation (Zhong et al. 2023); green finance, through policy guidance and financial support, promotes the upgrading of industrial structures toward greener orientations (Chen et al. 2023); furthermore, fintech mitigates the idiosyncratic risks and transactional costs of ecological shifts via technological empowerment, thereby catalyzing green transformation (Wu et al. 2024). Moreover, the strategic rollout of the Belt and Road Initiative (Wang and Cheng 2024), the expansion of digital financial inclusion (Fu et al. 2024), and the disciplinary pressures exerted by climate risk exposure (Fang 2023) have all been empirically documented to bolster environmental transitions at the firm level.

Nevertheless, some studies point out that green innovation, as the core pillar of green transformation, is often hindered by pronounced financing constraints and high trial-and-error costs (Noailly and Smeets 2022). Green innovation requires substantial and sustained capital investment in green technologies and research and development throughout the process (Xiang et al. 2022). Such investments are characterized by long payback periods, high technological uncertainty, and ambiguous short-term economic benefits, hindering enterprises' access to adequate external financing. More importantly, existing financing constraints directly weaken enterprises' enthusiasm and capacity to conduct green innovation activities, thereby stifling green innovation pathways and impeding ecological development targets (Yu et al. 2021). Under these circumstances, corporate green initiatives are largely tethered by financial limitations. Therefore, it is imperative to explore targeted financial support mechanisms to break through these financing bottlenecks.

With the deepening of research, DGST has gradually become a focal issue in both academia and practice, characterized by a dynamic evolutionary relationship of interdependence, bidirectional empowerment, and integrated symbiosis between digitalization and greening (Liu et al. 2025; Alabdali et al. 2024). Previous research generally argues that DGST constitutes an important pathway for firms to attain high-caliber growth and foster nascent productive forces (Shan et al. 2025). At its core lies the deep coupling of digital and green technologies, which can effectively promote breakthroughs in key core technologies (Zheng et al. 2025) and enhance the efficiency of resource allocation (Wang and Dong 2024). In terms of interaction mechanisms, digital transformation provides technological support and efficiency gains for green transformation by improving production efficiency, optimizing value chain coordination, and strengthening pollution monitoring accuracy; conversely, green transformation induces iterative upgrading of digital technologies and guides digital infrastructure toward low-carbon development, thereby mitigating potential rebound effects in the digitalization process. Empirical evidence shows that DGST alleviates the negative consequences of resource misallocation and fosters environmentally oriented innovation practices (Ye et al. 2024). Through resource complementarity and sharing effects, it also amplifies the positive externalities of green innovation, facilitating firms' sustainable development.

Nonetheless, the existing literature remains limited in several respects. Much of the prior research emphasizes regional- or

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industry-level analyses at the macro level, whereas quantitative examinations of firm-level drivers and mechanisms underlying DGST remain insufficient. Specifically, there is a lack of systematic investigation into how intellectual property–based financing instruments, such as patent pledge financing, affect DGST, leaving substantial room for further exploration.

The existing literature on patent pledge financing, largely based on difference-in-differences (DID) models exploiting patent pledge policies, has documented its multidimensional positive effects on firm development. First, prior studies highlight its role in expanding financing channels. Patent pledge financing effectively broadens firms' access to external funding, reduces the cost of debt financing, and enlarges investment opportunities (Liu and Zhu 2025). By increasing the diversity and richness of collateral, it also mitigates information asymmetry in credit markets (Benmelech and Bergman 2009). Moreover, patent pledge financing significantly enhances firms' risk-taking capacity, particularly for those burdened by tight financing constraints or enriched with high human capital (Li, Wang, and You 2024), thereby laying a financial foundation for high-risk innovation and transformation activities. Beyond expanding financing channels, the literature further extends to its impact on digital innovation and green development, mainly in two respects. On the one hand, patent pledge financing acts as a powerful catalyst for corporate innovation: It not only incentivizes firms to increase R&D investment (Mann 2018; De Rassenfosse and Palangkaraya 2023) but also encourages them to focus on core businesses, reduce unrelated diversification, and enhance the allocation efficiency of innovation resources (Fan et al. 2024), although its impact on innovation exhibits an inverted U-shaped pattern (Li, Zhang, et al. 2024). On the other hand, patent pledge financing demonstrates notable green effects, promoting green innovation and fostering environmental entrepreneurship, thereby effectively reducing firms' pollutant and carbon emissions (Gong et al. 2024; Shi et al. 2025), and serving as an important financial driver of green transformation.

Compared with indirect financial instruments such as green credit, patent pledge financing directly uses intellectual property assets as collateral and thus provides more immediate incentives for innovation (Mann 2018). Its multiple effects in alleviating financing constraints, stimulating technological innovation, and promoting green development exhibit a natural alignment with the financial, technological, and low-carbon requirements of firms' DGST. In sum, although existing studies have separately examined the positive roles of patent pledge financing in corporate innovation and green development, they have yet to synthesize digital and green transition into a convergent analytical model. Or systematically investigate their synergistic transformation, leaving substantial room for further exploration, which this study aims to address.

2.2 | Direct Effect of Patent Pledge on Firms' DGST

Firms' DGST essentially represents a comprehensive fusion process in which digitalization and greening are interdependent, mutually reinforcing, and interactively evolving. Through effective bidirectional empowerment between the two systems, the dual dimensions achieve benign symbiotic development, with the core essence lying in the deep coupling and organic integration of digital and green technologies. This systematic transformation process requires sustained and stable investment in technological R&D, optimized resource allocation, and long-term strategic planning, whereas inherent risk aversion and internal resource dispersion often act as key restrictive factors hindering transformation progress (Alabdali et al. 2024; Liu et al. 2025). As a core and innovative mode of intellectual property–based financing, patent pledge financing breaks firms' traditional financing reliance on tangible assets, providing multidimensional supports for corporate DGST by optimizing internal resource allocation, enhancing endogenous risk-taking capacity, and leveraging innovation-oriented financial backing, thereby exerting a significant positive promoting effect on DGST. By enabling the market-oriented monetization of patent intangible assets, patent pledge not only supplies stable capital funds to alleviate corporate innovation financing pressures but also guides firms to concentrate on core development areas and reduce inefficient resource wastage caused by unrelated business diversification (Fan et al. 2024). This rational optimization of resource allocation facilitates the concentration of limited corporate resources on the advancement of DGST, enabling digital-centric green production and real-time environmental surveillance, and provides essential financial and resource backing for technological R&D activities, which indirectly promotes the integrated innovation of digital and green technologies. Existing empirical evidence confirms that patent pledge effectively drives corporate technological innovation activities and reduces firms' pollutant emissions (Gong et al. 2024; Shi et al. 2025). Combined with the typical resource-focusing effect, this innovative operating mechanism further strengthens the intrinsic developmental momentum of firms' DGST.

DGST inherently involves the continuous exploration and practical application of new technologies and innovative business models, inevitably exposing firms to multiple operational risks such as rapid technological iteration, high trial-and-error costs, and intense market uncertainty, which easily fosters corporate risk-averse behavior and further constrains the overall transformation process (Martínez-Ros and Kunapatarawong 2019). Patent pledge financing, by improving firms' internal resource reserves and future growth expectations, significantly enhances their comprehensive risk-taking capacity (Li, Wang, and You 2024), enabling firms to more willingly and effectively engage in high-investment, high-return DGST projects and to proactively bear potential risks associated with R&D failures, equipment upgrades, and other transformation-related economic losses. At the same time, the sufficient financial and technological support provided by patent pledges reduces the technological uncertainty embedded in DGST and, when combined with sound innovation-financing safeguards, further alleviates various restrictive constraints during the whole transformation process.

In summary, patent pledge financing can effectively help firms overcome multiple latent barriers in the implementation of DGST, leading to the following research hypothesis H1:

H1. *Patent pledge financing has a positive effect on firms' DGST.*

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2.3 | Financing Constraints Mechanism

Financing constraints constitute a pivotal bottleneck that impedes firms' DGST, primarily because the essence of DGST necessitates a profound integration of digital and ecological technologies—a process characterized by high capital intensity and risk. Both digital transformation—requiring the introduction of digital technologies, infrastructure development, and application promotion—and green transformation—relying on green technology R&D, low-carbon process upgrades, and environmental equipment enhancement—demand substantial and sustained financial investment. Enterprises operating under rigorous external credit constraints frequently find technological integration and R&D expenditures financially prohibitive, resulting in stalled or halted transformation processes (Chen et al. 2021). This challenge is particularly pronounced for innovative firms, whose core assets are largely intangible, such as patents, with relatively low proportions of tangible assets. Under traditional financing models, such intangible assets are difficult to monetize as effective collateral. Coupled with China's bank-dependent corporate financing structure (Allen et al. 2005), the traditional credit preference for tangible assets exacerbates the funding gap and financing pressure in DGST (Hall 2002). As a core mode of intellectual property–based financing, patent pledge precisely addresses the financing needs of intangible assets and, compared with conventional financial instruments, more accurately aligns with the funding requirements of technological innovation and transformation (Mann 2018).

The core advantage of patent pledge financing lies in its ability to break the traditional reliance on tangible assets, transforming firms' patent-based intangible assets into pledgeable and monetizable financial assets. This effectively broadens firms' financing channels and resolves the difficulty of leveraging intangible assets for funding (Hochberg et al. 2018). Existing studies show that patent pledge financing not only significantly reduces firms' debt financing costs but also expands investment opportunities, providing stable and sustainable funding for various transformation activities (Liu and Zhu 2025). At the same time, patent pledge can reduce the risks and uncertainties, thereby incentivizing increased R&D investment and promoting corporate innovation (Mann 2018), offering both financial and technological support for DGST. By alleviating financing constraints, patent pledge directly addresses the barriers firms face due to insufficient funds, which otherwise hinder investments in digital technology applications and green innovation. It enables firms to allocate sufficient resources to digital infrastructure construction and digital-centric R&D and deployment, alongside executing green innovation initiatives, updating environmental equipment, and promoting low-carbon production practices, thereby underpinning the synergistic evolution of digital and green technologies with a robust fiscal framework. In summary, by alleviating capital scarcity, patent-backed financing propels the DGST process, leading to the H2:

H2. *Patent pledge financing can promote firms' DGST by alleviating financing constraints.*

2.4 | Innovation Structure Mechanism

The optimization of innovation structure constitutes a core foundation for firms' DGST, and patent pledge financing can facilitate this by guiding the allocation of innovation resources and focusing on key innovation areas, thereby providing technological support and advancing the transformation process. DGST fundamentally involves the deep integration of digital and green technologies, and its progress heavily depends on firms' technological accumulation in both domains. The presence of digital and green innovations within the innovation structure directly determines the technological basis and efficiency of DGST. Since technology investments are typically closely linked to overall commitments to sustainability (Yuan et al. 2023), patent pledge not only provides funding support for innovation activities but also strengthens firms' technological innovation orientation, encouraging the reduction of unrelated diversification and concentrating limited innovation resources on core areas (Fan et al. 2024). Empirical studies confirm that patent pledge significantly promotes green innovation and increases green patent outputs (Gong et al. 2024; Shi et al. 2025), while also enhancing R&D efficiency and supporting digital technology–related innovation and patent development (Mann 2018; De Rassenfosse and Palangkaraya 2023). These dual effects effectively increase the share of digital and green patents in total patent portfolios, thereby optimizing the overall innovation structure.

An optimized innovation structure aligns precisely with the technological demands of DGST, facilitating the deep coupling of digital and green technologies. Digitalization is closely linked to sustainability (Pan et al. 2022), and increased digital capacity strengthens firms' technological support, enabling the optimization of production processes and providing assurance for green development (Sun et al. 2024). Meanwhile, increased green innovation promotes the development and application of environmental technologies, embedding green value into digital transformation and fostering more environmentally oriented innovation practices (Ye et al. 2024). In addition, the enhanced risk-taking capacity afforded by patent pledge financing (Li, Wang, and You 2024) encourages firms to make long-term investments in digital and green innovation, further consolidating the benefits of innovation structure optimization and amplifying its impact on DGST. Accordingly, the following hypothesis is proposed:

H3. *Patent pledge financing can promote firms' DGST by optimizing their innovation structure.*

2.5 | Managerial Incentives Mechanism

Managerial incentives constitute an important internal driver of firms' DGST. As a long-term strategic transformation involving the deep integration of digital and green technologies, DGST requires managers to continuously allocate resources toward innovation activities whose outcomes are uncertain and whose benefits often materialize only in the long run (Alabdali et al. 2024; Liu et al. 2025). However, because of high

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technological uncertainty, substantial upfront investment requirements, and considerable risk exposure, managers may exhibit short-term preferences and become reluctant to undertake transformation projects with uncertain returns (Martínez-Ros and Kunapatarawong 2019).

Patent pledge financing can strengthen managerial incentives to engage in DGST through several channels. By converting patent assets into pledgeable collateral, patent pledge financing provides firms with additional financial resources and improves their ability to withstand transformation-related risks. Existing studies suggest that patent pledge financing enhances firms' risk-taking capacity and supports innovation-oriented activities (Mann 2018; Li, Wang, and You 2024). Improved resource availability and stronger risk-bearing capability reduce managerial concerns regarding potential failures associated with digital and green transformation projects, thereby encouraging managers to pursue long-term strategic investments. Moreover, patent pledge financing promotes firms' focus on core businesses and reduces inefficient diversification (Fan et al. 2024), helping align managerial decision-making with long-term value creation objectives. As DGST itself represents a strategic process that relies on sustained commitment to digital and green innovation, stronger managerial incentives are expected to facilitate the implementation and persistence of such transformation activities.

Accordingly, the following hypothesis is proposed:

H4. *Patent pledge financing can promote firms' DGST by strengthening managerial incentives.*

3 | Methods

3.1 | Model Specification

3.1.1 | Baseline Regression Model

To examine the effect of patent pledge financing on firms' DGST, this study constructs the model in Equation (1) for analysis.

$$coordination_{i,t} = \beta_0 + \beta_1 lnpp_{i,t} + \gamma control_{i,t} + u_i + \eta_t + \varepsilon_{i,t} \quad (1)$$

where $coordination_{i,t}$ represents the level of DGST for firm i in year t, $lnpp_{i,t}$ denotes the amount of patent pledge for firm i in year t, and $control_{i,t}$ is a set of firm-level control variables. u_i and η_t represent firm and year fixed effects, respectively, and $\varepsilon_{i,t}$ is the random error term. A significantly positive estimate of β_1 would indicate that patent pledge financing contributes to the enhancement of firms' DGST.

3.2 | Variable Definitions

3.2.1 | Dependent Variable

$coordination_{i,t}$ serves as the dependent variable, which is measured using a coupling coordination degree model. First, following Fang et al. (2026), a corporate digital transformation index is constructed from four dimensions. Each dimension level is quantified using word frequency analysis of annual reports. Second, a corporate green transformation index is constructed. The green transformation level draws on Loughran and Mcdonald (2011), employing text analysis to select 113 green transformation–related keywords and calculate their word frequency based on sources such as annual reports. Finally, the coupling coordination degree of DGST is calculated.

To eliminate differences in measurement scales, the raw data are first normalized using range standardization, and the standardized data are then applied to the adjusted coupling coordination model for computation.

$$coupling = \sqrt{\left[1 - (U_2 - U_1)\right] \times \frac{U_1}{U_2}} \quad (2)$$

$$T = \alpha_1 \times U_1 + \alpha_2 \times U_2 \quad (3)$$

$$coordination = \sqrt{coupling \times T} \quad (4)$$

In Equations (2–4), it is assumed that $U_2 > U_1$, where U_1 and U_2 represent the smaller and larger values, respectively, of firm i's digital transformation index and green transformation index in year t. The variable *coupling* measures the degree of interaction between the two systems for the firm. The closer the link between digitalization and greening, the higher the *coupling* value; conversely, a weaker connection results in a lower *coupling* value. T denotes the comprehensive evaluation index. The parameters α_1 and α_2 are weighting coefficients representing the relative importance of the DGST. In the baseline model, digital and green transformation are assumed equally important, i.e., $\alpha_1 = \alpha_2 = 0.5$. The variable *coordination* represents the coupling coordination degree between DGST for firm i in year t and serves as the dependent variable.

3.2.2 | Key Explanatory Variable and Control Variables

The key explanatory variable in this study is constructed based on firms' patent pledge activities with registered and effective patent pledge contracts, calculated as the natural logarithm of the annual number of patents under effective pledge registration plus one. In the robustness tests, this study further employs regional patent pledge policies as the key explanatory variable. We also explore patent pledge activities that involve cancellation of registered patent pledge contracts in the heterogeneity analysis of patent pledge attributes.

The patent pledge financing data used in this study were obtained from the "Patent Pledge and Litigation (PPLD)–Listed Company Patent Pledges" database provided by the China Research Data Services Platform (CNRDS). This database is constructed based on patent pledge registration records publicly disclosed by the China National Intellectual Property Administration (CNIPA) and covers all valid patent pledge registrations involving Chinese A-share listed companies and their affiliated entities during the period 2010–2022. It contains detailed information on both pledgors and pledgees,

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TABLE 1 | Data matching and processing procedure.

Step	Procedure	Detailed processing
1	Raw data collection	Collect all patent pledge registration records involving A-share listed companies from 2010 to 2022. Key fields include pledging parties, patent application numbers, authorization announcement dates, registration effective dates, and legal status.
2	Entity matching and consolidated reporting identification	(1) Direct pledge records: The pledgor's name is exactly matched with the listed company's registered name. (2) Affiliated entity pledge records: Subsidiaries, associates, and joint ventures within the scope of consolidated financial statements are identified through the CNRDS affiliated enterprise database. (3) Cross-validation: Ownership relationships are verified using patent application numbers and patent owner information.
3	Screening by patent legal status	(1) Retain records with the status "Patent Pledge Contract Registration Effective" and exclude invalid or cancelled records. (2) Use legal status, authorization announcement dates, and registration effective dates to identify authorized patent pledges, requiring that the authorization date precedes the pledge registration date. (3) Separately extract records with the status "Patent Pledge Contract Registration Cancellation" for placebo tests.
4	Removal of duplicate and abnormal records	(1) Remove duplicate observations using the combination of patent application number, registration effective date, and pledgee name as a unique identifier. (2) Exclude observations with ambiguous pledgor names, missing patent application numbers, or abnormal pledge status.
5	Firm-year data aggregation	(1) Aggregate all valid patent pledge records at the firm-year level using listed company stock code and year as unique identifiers. (2) Count the number of pledged authorized patents and construct the core explanatory variable, *lnpp*, defined as the natural logarithm of the annual number of pledged patents plus one.
6	Heterogeneity tagging and alternative variable construction	(1) Classify pledged patents as green or digital patents according to IPC classifications. (2) Distinguish invention patents, utility models, and design patents based on patent application information. (3) Construct alternative patent pledge indicators for heterogeneity and robustness analyses.

patent application numbers, authorization announcement dates, registration effective dates, legal status, and other key characteristics of patent pledge transactions.

The specific procedures for data matching and processing are summarized in Table 1.

The control variables include a set of firm-level indicators: (i) firm age (*firmage*), measured as the logarithm of the number of years since establishment; (ii) inventory ratio (*inv*), calculated as the ratio of net inventory to total assets; (iii) leverage (*lev*), measured as the ratio of total liabilities to total assets; (iv) cash flow ratio (*cashflow*), calculated as net operating cash flow divided by total assets; (v) total asset turnover (*ato*), measured as total sales revenue divided by average total assets; (vi) return on assets (*roa*), calculated as net profit divided by total assets; and (vii) firm assets (*assets*), measured as the logarithm of total assets.

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3.2.3 | Sample and Data Description

This study uses Chinese A-share listed companies from 2010 to 2022 as the research sample. The following observations are excluded: nonlisted firms, financial industry firms, ST/*ST/PT firms, firms with nonnormal listing status.[1] Data are sourced from the CSMAR database, CNRDS database, corporate annual reports, the *China Statistical Yearbook*, and local government work reports. To mitigate the influence of outliers, all continuous variables are winsorized at the 1% level on both tails. Descriptive statistics of the sample are presented in Table 2.

The descriptive statistics of the DGST show that the sample mean is 0.292, the standard deviation is 0.085, the minimum value is 0.000, and the maximum value is 0.887. The value range of the variables conforms to the theoretical scope of the coupling coordination degree, with no extreme outliers and reasonable distribution characteristics. This indicates that the measurement results are sound and robust and can provide reliable data support for subsequent empirical analysis.

4 | Results and Discussion

4.1 | Baseline Regression Results

Columns (1–4) in Table 3 present the effects of patent pledge financing on firms' DGST. Across all specifications—from the simplest model to those including control variables and firm and year fixed effects—the estimated coefficient of *lnpp* stays positive and maintains significance at the 5% level or better. This indicates that firms' patent pledge financing effectively promotes the advancement of DGST.

4.2 | Robustness Tests

4.2.1 | Alternative Measurement of the Dependent Variable

First, replacing the coordination degree with the coupling degree does not alter the significance of our main findings (Table 4, Column 1). To ensure the DGST index is not driven

TABLE 2 | Summary statistics.

VarName	Obs	Mean	SD	Min	Max
coordination	28,429	0.2924	0.0854	0	0.8874
lnpp	28,429	0.0790	0.3832	0	4.2341
assets	28,429	22.2814	1.2983	17.4260	28.6067
lev	28,429	0.4346	0.2109	0.0075	3.5130
roa	28,429	0.0367	0.0810	−1.8591	1.2848
ato	28,429	0.6499	0.5495	−0.0479	12.3729
firmage	28,429	2.9428	0.3344	0.6931	4.2341
cashflow	28,429	0.0454	0.0754	−1.9377	0.8385
inv	28,429	0.1439	0.1351	0	0.9426

TABLE 3 | Baseline regression.

	(1)	(2)	(3)	(4)
	coordination	*coordination*	*coordination*	*coordination*
lnpp	0.0035***	0.0019**	0.0154***	0.0029***
	(0.0009)	(0.0009)	(0.0018)	(0.0009)
cons	0.2921***	−0.4353***	0.2928***	−0.1188***
	(0.0001)	(0.0299)	(0.0221)	(0.0394)
Control	No	Yes	Yes	Yes
Firm effect	Yes	Yes	No	Yes
Year effect	Yes	No	Yes	Yes
N	28,429	28,429	28,429	28,429
Adj. R^2	0.768	0.768	0.142	0.776

Note: The robust standard errors that cluster to the firm are in parentheses. Unless otherwise specified, the same applies to the following table.
***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

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TABLE 4 | Robustness tests.

	(1) *coupling*	(2) *coordination_w1*	(3) *coordination_w2*	(4) *coordination*	(5) *L.coordination*
lnpp	0.0034**	0.0029***	0.0028***		0.0026***
	(0.0015)	(0.0009)	(0.0009)		(0.0009)
did				0.0098*	
				(0.0054)	
cons	−0.2227***	−0.0828**	−0.1655***	−0.1269**	−0.0780*
	(0.0610)	(0.0399)	(0.0395)	(0.0501)	(0.0437)
Control	Yes	Yes	Yes	Yes	Yes
Firm effect	Yes	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes	Yes
N	28,429	28,429	28,429	28,429	22,375
Adj. R^2	0.705	0.763	0.790	0.776	0.786

Note: Column (4) clusters standard errors at the city level.

by specific weighting choices, we follow Pan et al. (2025) and recalculate DGST using polarized weightings of 1/3 and 2/3.[2] Empirical estimates in Table 4, Columns (2) and (3), validate that the *lnpp* persists at the 1% significance level across both specifications.

4.2.2 | Alternative Measurement of the Key Explanatory Variable

Following the approach of Xie et al. (2023), patent pledge is also measured using city-level patent pledge policies. Specifically, we construct a DID variable *did*, as the interaction of *treat* and *post*. *treat* = 1 if a firm is located in a patent pledge pilot city and 0 otherwise; *post* = 1 if the year falls after the policy implementation year and 0 otherwise. The regression results in Column (4) of Table 4 show that the key explanatory variable remains significant.

4.2.3 | Lagged Dependent Variable

Considering that DGST require a certain time to materialize, a robustness check is conducted by lagging the dependent variable, *coordination*, by one period. As detailed in Table 4, Column (5), the primary explanatory variable retains its significance at the 1% level.

4.3 | Endogeneity Analysis

When examining the effect of patent pledge financing on firms' DGST, endogeneity issues may arise due to unobserved firm characteristics, bidirectional causality, and sample self-selection. On one hand, firms that engage in patent pledges and pursue DGST may systematically differ in capabilities or technological endowments. Conversely, a reciprocal relationship may exist where DGST-intensive firms more readily leverage patent pledges, introducing simultaneity bias into the baseline estimates. To address these concerns, this study applies propensity score matching (PSM) to mitigate self-selection bias and employs two-stage least squares (2SLS) to further account for bidirectional causality and omitted variable problems.

First, PSM is conducted using 1:4 nearest-neighbor matching with a caliper of 0.05. The average treatment effect on the treated (ATT) after matching is reported in Column (1) of Table 5 and is significantly positive. Balance tests for the covariates confirm the validity of the matching procedure.

Second, using the regional average as an instrumental variable is a common approach (Kleis et al. 2012). Accordingly, this study selects the logarithm of the average patent pledge quantity of other firms in the same district or county as the instrument. The rationale is twofold: (i) A single firm's patent pledge activity is likely correlated with the average patent pledges of other firms in the same region, satisfying the relevance condition, as there may be positive demonstration effects or negative resource competition; (ii) the average patent pledges of other firms in the region are unlikely to directly affect an individual firm's DGST, approximately satisfying the exogeneity condition (Cheng et al. 2021). Based on this, 2SLS is used to estimate the effect of patent pledge on DGST. Columns (2) and (3) of Table 5 report the results, showing that the instrument passes weak instrument and underidentification tests. At the 1% significance level, patent pledge financing remains positively associated with firms' DGST.

4.4 | Mechanism Analysis

To examine the mediating roles of financing constraints, innovation structure and managerial incentives, this study constructs the models in Equations (5) to (7).

$$SA_{i,\ t} = \beta_0 + \beta_1 lnpp_{i,t} + \gamma control_{i,t} + u_i + \eta_t + \varepsilon_{i,t} \quad (5)$$

$$IS_{i,\ t} = \beta_0 + \beta_1 lnpp_{i,t} + \gamma control_{i,t} + u_i + \eta_t + \varepsilon_{i,t} \quad (6)$$

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$$Incentive_{i,\ t} = \beta_0 + \beta_1 lnpp_{i,t} + \gamma control_{i,t} + u_i + \eta_t + \varepsilon_{i,t} \quad (7)$$

where *SA* represents financing constraints, measured using the SA index constructed by Hadlock and Pierce (2010), with higher values indicating more severe financing constraints. *IS* denotes the firm's innovation structure, measured as the proportion of digital patents plus green patents in total patent grants for that year. *Incentive* following the measurement approach of Chava and Purnanandam (2010), this study constructs the management incentive variable based on executives' equity holdings. Specifically, Chava and Purnanandam (2010) measure the increase in executives' wealth resulting from a 1% increase in the firm's stock price, using the value appreciation of all executive stock and option holdings to capture the alignment of interests between managers and shareholders. Given the substantial variation in annual executive compensation across firms, this study standardizes the incentive sensitivity measure by defining managerial incentives as the ratio of the increase in the value of executives' stock and option holdings associated with a 1% increase in the firm's stock price to executives' total annual compensation. A higher ratio indicates stronger performance-based incentives for management. All other variables are defined as in Equation (1).

TABLE 5 | Endogeneity analysis.

	(1) PSM *coordination*	(2) First stage *lnpp*	(3) Second stage *coordination*
ATT	0.0476***		
	(0.0029)		
lnpp_mean		0.9988***	
		(0.0310)	
lnpp			0.0044***
			(0.0016)
cons	0.1283***	/	/
	(0.0029)	/	/
F-statistic	/	1038.88	/
Kleibergen–Paap rk LM statistic	/	/	160.362
Kleibergen–Paap rk Wald *F*-statistic	/	/	1038.875
Control	Yes	Yes	Yes
Firm effect	Yes	Yes	Yes
Year effect	Yes	Yes	Yes
N	2866	28,429	28,429
Adj. R^2	/	/	0.037

The regression results, reported in Columns (1–6) of Table 6, indicate that patent pledge financing effectively alleviates financing constraints, improves the digital–green innovation structure and mangerial incentives, thereby promoting firms' DGST. These findings support Hypotheses H2, H3, and H4.

4.5 | Moderating Effect Analysis

When firms face higher debt risk constraints, both the resource availability and risk-taking incentives required for DGST may be restricted. As a result, the financing support provided by patent pledge financing may be less likely to be translated into effective transformation investments, thereby weakening its positive effect on DGST. To examine this moderating mechanism, this study introduces firms' debt risk as a moderating variable and constructs Equation (8) to test its moderating effect.

$$coordination_{i,t} = \beta_0 + \beta_1 \left(lnpp_{i,t} \times \tau_{i,t}\right) + \beta_2 lnpp_{i,t} + \beta_3 \tau_{i,t} + \gamma control_{i,t} + u_i + \eta_t + \varepsilon_{i,t} \quad (8)$$

TABLE 6 | Mechanism analysis.

	(1) *SA*	(2) *SA*	(3) *IS*	(4) *IS*	(5) *Incentive*	(6) *Incentive*
lnpp	−0.0077***	−0.0069***	0.0174***	0.0167***	0.0147***	0.0164***
	(0.0016)	(0.0016)	(0.0029)	(0.0029)	(0.0040)	(0.0041)
cons	−3.8459***	−3.7232***	0.2460***	−0.1762	0.2484***	0.1280
	(0.0001)	(0.1157)	(0.0002)	(0.1268)	(0.0003)	(0.1583)
Control	No	Yes	No	Yes	No	Yes
Firm effect	Yes	Yes	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes	Yes	Yes
N	28,429	28,429	28,429	28,429	28,429	28,429
Adj. R^2	0.954	0.954	0.686	0.687	0.795	0.801

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In Equation (8), $\tau_{i,t}$ firms' debt risk, whereas all other variables are defined consistently with Model (1). Two alternative measures of debt risk are employed.

First, following Bharath and Shumway (2008), we estimate firms' expected default frequency (edf) using a simplified Merton model. Specifically, the distance to default (DD) is calculated as Equation (9):

$$\mathrm{DD}_{i,t} = \frac{ln\left(V_{A,i,t}/D_{T,i,t}\right) + \left(\mu_{i,t} - \sigma^2_{A,i,t}/2\right)T_{i,t}}{\sigma_{A,i,t}\sqrt{T_{i,t}}} \tag{9}$$

where $V_{A,i,t}$ denotes the market value of firm assets and $D_{T,i,t}$ is measured as the sum of short-term debt and one-half of long-term debt. $\mu_{i,t}$ is proxied by the firm's stock return in the previous year, whereas $\sigma_{A,i,t}$ represents asset volatility obtained from a weighted combination of equity and debt volatility. The maturity horizon $T_{i,t}$ is set to 1 year. Based on the distance to default, the expected default frequency is calculated as $edf_{it} = N(-\mathrm{DD}_{i,t})$, where $N(\cdot)$ denotes the cumulative standard normal distribution function. A higher *edf* indicates a greater risk of debt default.

Second, following Zhang et al. (2010), we construct an alternative debt risk indicator (*Z*-score) as 0.517 minus 0.46 times the ratio of total liabilities to total assets, minus 0.388 times the ratio of working capital to total assets, plus 9.32 times the ratio of net profit to average total assets, and plus 1.158 times the ratio of retained earnings to total assets. This measure has been widely used in studies of debt risk among Chinese firms (Guan et al. 2016; Shahab et al. 2018). A higher *Z*-score indicates a lower probability of debt default.

To test the moderating effect, the mean-centered core explanatory variable is interacted with the mean-centered debt risk measures, generating two interaction terms, *inter1* and *inter2*, respectively. Based on the construction of the two debt risk measures, a negative moderating effect of debt risk would be reflected by a significantly negative coefficient on *inter*1 and a significantly positive coefficient on *inter*2.

The estimation results are reported in Columns (1–4) of Table 7. Regardless of whether control variables are included, debt risk exhibits a significant negative moderating effect. Specifically, the higher the debt risk faced by a firm, the weaker the positive impact of patent pledge financing on DGST.

4.6 | Heterogeneity Analysis

4.6.1 | Firm-Level Heterogeneity

Considering that patent pledge financing may have heterogeneous effects on firms' DGST, we conduct a heterogeneity analysis based on whether firms belong to high-tech industries, the quality of bank–firm relationships, and firm size. Bank–firm relationships are coded as 1 if any of the following conditions are met: The bank holds shares in the firm, the firm holds shares in the bank, or top management has a banking background; otherwise, the value is 0. Firms belonging to high-tech industries are coded as 1, and

TABLE 7 | Moderating effect of debt risk.

	(1)	(2)	(3)	(4)
	coordination	***coordination***	***coordination***	***coordination***
lnpp	0.0028***	0.0022**	0.0039***	0.0032***
	(0.0009)	(0.0009)	(0.0009)	(0.0009)
edf	0.0056**	−0.0069***		
	(0.0024)	(0.0024)		
inter1	−0.0150***	−0.0146***		
	(0.0030)	(0.0030)		
Zscore			0.0003	−0.0020
			(0.0006)	(0.0014)
inter2			0.0026***	0.0023***
			(0.0008)	(0.0007)
cons	0.2910***	−0.1273***	0.2918***	−0.1199***
	(0.0005)	(0.0395)	(0.0005)	(0.0394)
Control	Yes	Yes	Yes	Yes
Firm effect	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes
N	28,429	28,429	28,429	28,429
Adj. R^2	0.768	0.776	0.768	0.776

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all others as 0. Firm size is classified by the average number of employees.

The regression results, reported in Columns (1–6) of Table 8, show that patent pledge financing has a more pronounced effect on promoting DGST for high-tech firms, large-sized firms, and firms with strong bank–firm relationships.

In terms of bank–firm relationship heterogeneity, the coefficient of the core explanatory variable *lnpp* is 0.0045 and significantly positive at the 1% level for firms with close bank–firm ties. For firms with weak bank–firm relationships, the coefficient is 0.0023, only significant at the 5% level. The economic effect of patent pledge financing in firms with close bank connections is nearly twice that of their counterparts, with higher statistical significance. This indicates that deeper bank–firm linkages amplify the positive effects of patent pledge financing. By reducing information asymmetry and enhancing banks' recognition of firms' innovative assets, close bank–firm relationships help convert patent pledge funds more effectively into investment for DGST.

In terms of industry technological heterogeneity, *lnpp* yields a significant positive coefficient of 0.0024 at the 5% level for high-tech firms, whereas the coefficient is 0.0022 and only significant at the 10% level for non-high-tech firms. Accordingly, high-tech firms exhibit stronger and more significant patent pledge financing effects. Because of their technology-oriented competitiveness, high-tech firms can better convert patent financing into digital–green upgrading. In contrast, non-high-tech firms have lower patent value and weaker transformation incentives, which weaken the promotional effect of patent pledge financing.

In terms of firm size heterogeneity, *lnpp* yields a significant positive coefficient of 0.0028 at the 1% level for large-size firms, whereas the coefficient is 0.0014 and statistically insignificant for small-size firms. Accordingly, large-size firms exhibit stronger and more significant patent pledge financing effects. Because of their stronger resource endowments and operational capabilities, large firms can more effectively deploy patent pledge financing to support digital–green upgrading. In contrast, small firms face greater financing constraints and weaker risk-bearing capacity, which limit their ability to translate patent financing into tangible DGST progress.

Overall, the facilitating effect of patent pledge financing on corporate DGST is stronger and more significant for firms with close bank–firm relationships and high-tech and larger size attributes, which is highly consistent with theoretical expectations.

The high-tech firms typically hold more patents and face more severe financing constraints (Hall 2002). Moreover, high-tech firms possess richer patent reserves and stronger capabilities to absorb and transform technology, enabling them to leverage patent pledges more effectively for financing and innovation incentives, thereby accelerating DGST. In addition, banks play an important role in supporting sustainable development (Rataj et al. 2024). Firms with closer bank–firm relationships experience lower information asymmetry and financing frictions, allowing them to access funds through patent pledges more smoothly and providing stable support for DGST.

4.6.2 | Regional Heterogeneity

Considering that patent pledge financing may have heterogeneous effects on firms' DGST across regions, this study explores heterogeneity by partitioning the sample according to city-level green attention and digital infrastructure. City green attention is measured following Tu et al. (2024) by calculating the word frequency of green development–related terms in local government reports. Cities are split into high- and low-green-attention groups based on whether they surpass or fall behind the median. City digital infrastructure is measured following Wang et al. (2024), using the word frequency of terms related to new infrastructure construction in local government reports. Cities are dichotomized into

TABLE 8 | Firm-level heterogeneity.

	(1)	(2)	(3)	(4)	(5)	(6)
	High bank–firm relationship	**Low bank–firm relationship**	**High-tech industry firms**	**Non–high-tech industry firms**	**Large size firms**	**Small size firms**
	coordination	***coordination***	***coordination***	***coordination***	***coordination***	***coordination***
lnpp	0.0045***	0.0023**	0.0024**	0.0022*	0.0028***	0.0014
	(0.0016)	(0.0010)	(0.0012)	(0.0011)	(0.0010)	(0.0016)
cons	−0.1107*	−0.0726	−0.1066*	−0.1397***	−0.0805	−0.1013
	(0.0635)	(0.0533)	(0.0595)	(0.0522)	(0.0538)	(0.0627)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Firm effect	Yes	Yes	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes	Yes	Yes
N	9259	18,265	13,834	14,541	15,324	12,680
Adj. R^2	0.770	0.796	0.828	0.663	0.813	0.768

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TABLE 9 | Regional heterogeneity.

	(1)	(2)	(3)	(4)
	High green development attention	**Low green development attention**	**High digital infrastructure level**	**Low digital infrastructure level**
	coordination	***coordination***	***coordination***	***coordination***
lnpp	0.0025**	0.0023*	0.0044***	0.0010
	(0.0011)	(0.0013)	(0.0011)	(0.0014)
cons	−0.0993*	−0.1311***	−0.1038*	−0.1452***
	(0.0540)	(0.0494)	(0.0532)	(0.0552)
Control	Yes	Yes	Yes	Yes
Firm effect	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes
N	13,979	13,332	14,016	13,763
Adj. R^2	0.811	0.734	0.760	0.810

high- and low-digital infrastructure cohorts based on the median threshold.

The regression results, reported in Columns (1–4) of Table 9, show that patent pledge financing has a more pronounced effect on DGST for firms located in cities with high green development attention and for firms in cities with advanced digital infrastructure. Firms in high-green-attention regions tend to have stronger green transformation willingness and supportive industrial ecosystems, allowing the financing provided by patent pledges to precisely meet their funding needs for green technology R&D and digital upgrades. For firms in cities with high digital infrastructure levels, the well-developed digital technology support and application scenarios improve existing production and operational processes, reduce regional carbon emissions (Tang and Yang 2022), and reshape the firms' value creation chains (Huang et al. 2017). This enables firms to more efficiently convert resources obtained through patent pledges into integrated digital–green practices while leveraging data sharing and process optimization to lower the trial-and-error and coordination costs of DGST, further enhancing the role of patent pledges in alleviating financing constraints and incentivizing technological innovation, thereby fully unlocking the potential of DGST.

4.6.3 | Heterogeneity in Patent Pledge Characteristics

To further explore the potential influence of patent heterogeneity, this study classifies patent pledge financing according to patent technological attributes, patent types, and pledge validity. The results are reported in Table 10.

First, based on IPC classifications, patent pledges are distinguished into green patent pledges and digital patent pledges. The identification of digital patent pledges follows the *Correspondence Table between Core Digital Economy Industries and International Patent Classification (IPC) Codes (2023)* issued by the CNIPA. Patent pledge records are matched with the relevant IPC codes to identify patents related to digital technologies. The variable *lnDpp* is constructed as the natural logarithm of one plus the annual number of digital patent pledges. Similarly, green patent pledges are identified according to the *Green and Low-Carbon Technology Patent Classification System* published by the CNIPA. The variable *lnGpp* is defined as the natural logarithm of one plus the annual number of green patent pledges.

Columns (1–2) of Table 10 show that the coefficients of both green patent pledges (*lnGpp*) and digital patent pledges (*lnDpp*) are significantly positive at the 1% level. This finding suggests that both types of patent pledges effectively promote firms' DGST. The significance of both effects further indicates that green technological assets and digital technological assets are not independent drivers of corporate transformation; rather, they reinforce each other. Green patent pledges provide financial support for low-carbon transformation and facilitate the adoption of digitally enabled green production technologies, whereas digital patent pledges support intelligent upgrading and improve the efficiency of green technology applications. Together, they contribute to the deep integration of digitalization and greening.

Second, based on patent application information, pledged patents are further classified into invention patents, utility model patents, and design patents. Accordingly, three variables are constructed: *lnInvpp*, *lnUtilpp*, and *lnDespp*, measured as the natural logarithm of one plus the annual number of pledged invention patents, utility model patents, and design patents, respectively. Among these categories, invention patents generally possess the highest technological content and economic value, allowing firms to obtain substantially larger amounts of financing through patent pledge arrangements.

Columns (3–5) of Table 10 show that the coefficient of invention patent pledges (*lnInvpp*) is significantly positive at the 1%

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TABLE 10 | Heterogeneity in patent pledge characteristics.

	(1)	(2)	(3)	(4)	(5)	(6)
	Green patent pledge	**Digital patent pledge**	**Invention patent pledge**	**Design patent pledge**	**Utility model patent pledge**	**Cancellation of patent pledge**
	coordination	***coordination***	***coordination***	***coordination***	***coordination***	***coordination***
lnGpp	0.0095***					
	(0.0024)					
lnDpp		0.0054***				
		(0.0017)				
lnInvpp			0.0033***			
			(0.0010)			
lnDespp				0.0045		
				(0.0063)		
lnUtilpp					0.0018	
					(0.0011)	
lnCpp						0.0012
						(0.0011)
cons	−0.1207***	−0.1202***	−0.1189***	−0.1218***	−0.1205***	−0.1211***
	(0.0393)	(0.0393)	(0.0393)	(0.0392)	(0.0394)	(0.0393)
Control	Yes	Yes	Yes	Yes	Yes	Yes
Firm effect	Yes	Yes	Yes	Yes	Yes	Yes
Year effect	Yes	Yes	Yes	Yes	Yes	Yes
N	28,429	28,429	28,429	28,429	28,429	28,429
Adj. R^2	0.776	0.776	0.776	0.776	0.776	0.776

level, whereas the coefficients of utility model patent pledges and design patent pledges are statistically insignificant. These results indicate that only invention patent pledges, which possess higher technological value, stronger legal protection, and greater financing capacity, can effectively promote DGST. This finding also suggests that patent pledge financing requires a sufficient and stable amount of funding to support digital–green transformation. In contrast, pledging a large number of relatively low-value utility model patents generates only limited financing support and therefore has little impact on transformation outcomes.

Finally, to rule out the possibility that the baseline results are driven by firms' patent stock or innovation capability rather than actual financing effects, we construct an alternative variable (*lnCpp*) using the natural logarithm of one plus the annual number of patent pledge contracts with a registration status of "cancellation." This variable replaces the baseline patent pledge measure (*lnpp*), which is based on effective patent pledge registrations. Since cancelled patent pledges represent contracts that were either not executed or subsequently terminated, firms do not obtain substantial financing support from them. Therefore, such pledges should not exert a significant influence on corporate transformation.

As reported in Column (6) of Table 10, the coefficient of cancelled patent pledges is statistically insignificant. This result effectively rules out alternative explanations related to firms' innovation capability and further supports the causal interpretation of the baseline findings.

Overall, the analyses based on patent technological attributes, patent types, and pledge validity provide strong evidence for the robustness of the core conclusions. These findings offer additional empirical support for the proposed mechanisms and the validity of the key explanatory variables employed in this study.

5 | Conclusions and Policy Implications

5.1 | Conclusions

Utilizing a panel of 28,429 observations from Chinese firms, we provide an empirical assessment of how patent pledge financing influences firms' DGST. Our analysis yields the following core conclusions:

1. Patent pledge financing exerts a positive influence on the DGST. By prioritizing the integrated evolution of

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digital and environmental capabilities, our empirical evidence underscores that patent pledges—acting as a critical modality of intellectual property-based intermediation—effectively bolster firms' DGST. This indicates that by converting intangible assets into actual financing capacity, firms can support digital technology adoption, green innovation practices, and their integration. The findings highlight the critical role of IP-based finance in overcoming funding constraints and stimulating transformation momentum, providing empirical evidence that firms can leverage patent assets to achieve high-quality transformation.

2. Patent pledges drive DGST primarily by easing financial constraints, optimizing innovation structures, and enhancing managerial incentives. Mechanism analysis reveals three main pathways: (i) relieving financing constraints—patent pledges break the traditional dependence on tangible assets by converting patents into collateralizable financial assets, thereby broadening financing channels, reducing financing costs, and providing stable funding for digital infrastructure construction, green technology R&D, and other transformation activities; (ii) optimizing innovation structure—patent pledges strengthen firms' innovation incentives, guiding the allocation of resources toward digital and green patents, improving innovation resource efficiency, and creating a solid technical foundation for the deep integration of digital and green technologies; and (iii) enhancing managerial incentives—patent pledges strengthen managerial incentives, thereby further promoting DGST. These three mechanisms constitute the intrinsic logic through which patent pledges facilitate DGST.

3. The effect of patent pledges on DGST exhibits significant heterogeneity. Heterogeneity analyses indicate that the transformational effect of patent pledges varies across firms and regions. At the firm level, high-tech firms, with richer patent reserves and stronger technological absorption capabilities, can leverage patent pledges more efficiently to advance DGST; firms with strong bank–firm relationships benefit from lower information asymmetry and easier access to financing, enhancing the effect of patent pledges; large-size firms, with stronger resource endowments and operational resilience, are better positioned to translate patent pledge financing into tangible digital–green progress, whereas small firms face tighter financing constraints that limit such transformative effects. At the regional level, firms in cities with higher green development attention are more likely to channel patent pledge funds into integrated digital–green projects due to supportive policies and market preferences; firms in regions with advanced digital infrastructure can reduce coordination costs and amplify the transformation-enabling effect of patent pledges, leveraging strong digital technology support to maximize the impact on DGST.

4. The effectiveness of patent pledge financing depends on firms' financial conditions and the characteristics of pledged patents. Additional analyses show that debt default risk negatively moderates the relationship between patent pledges and DGST, suggesting that high debt risk weakens firms' ability to translate patent-backed financing into transformation investments. Furthermore, both digital patent pledges and green patent pledges significantly promote DGST, highlighting the complementary roles of digital and green technological assets in supporting the twin transition. However, only invention patent pledges generate a significant positive effect, whereas utility model and design patent pledges fail to promote DGST. This finding suggests that the transformational benefits of patent pledge financing depend on the technological value and financing capacity of pledged patents, as substantial and stable financing support appears necessary for digital–green transformation. Finally, placebo tests based on cancelled patent pledge registrations show no significant effect on DGST, further strengthening the causal interpretation and robustness of the baseline findings.

5.2 | Policy Recommendations

1. In light of the positive effect of patent pledges on DGST, the IP pledge financing framework should be further enhanced. On one hand, the patent valuation system should be optimized by cultivating specialized patent appraisal institutions and establishing multi-dimensional standards that account for both technological and market value, thus narrowing the transparency gap separating financial intermediaries from enterprises. On the other hand, the coverage of patent pledge financing should be expanded. Financial institutions should be encouraged to develop pledge financing products tailored to DGST needs, streamline approval processes, and offer preferential pledge interest rates to firms undertaking DGST, thereby improving firms' willingness to utilize patent pledges and fully unlocking the financing potential of patent assets.

2. Target policy measures to alleviate financing constraints, optimize innovation structure, and strengthen managerial incentives. To relieve financing constraints, a risk compensation fund for patent pledge financing should be established to partially cover losses for financial institutions, reducing lending risks. Government-backed financing guarantee institutions should also provide guarantees for patent pledge loans, further expanding firms' access to capital. To optimize innovation structure, support for digital and green R&D should be intensified, integrating patent pledge financing with R&D subsidies and tax incentives, guiding firms to allocate pledged funds toward integrated digital–green innovation. Additionally, patent technology exchange platforms should be established to facilitate the conversion and application of digital and green patents, enhancing the market value of innovation outcomes. To strengthen managerial incentives, firms should improve long-term incentive schemes by linking managerial compensation to DGST performance.

3. Given firm heterogeneity and regional disparities, local governments should implement more targeted supporting policies. For high-tech firms, governments can provide special fiscal subsidies and optimize intellectual property pledge regulatory systems by simplifying registration, valuation, and approval procedures, thereby encouraging the

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activation of digital and green patent assets and facilitating cross-domain innovation. For non-high-tech firms with weaker banking relationships, policy-based credit guarantee mechanisms, together with interest subsidies and improved patent valuation systems, can help reduce financing barriers and enhance access to patent pledge financing. For large firms, governments can leverage their scale advantages to drive industry-wide digital–green demonstration effects; for small firms, targeted streamlined processes and risk-sharing mechanisms can help ease their financing constraints.

At the regional level, policymakers should rationally prioritize and coordinate the deployment of green advocacy initiatives and digital infrastructure construction to create a supportive external environment for patent pledge financing to empower corporate digital–green transformation. Regions with insufficient green development awareness should strengthen public and industrial green publicity, formulate targeted incentive guidelines, and foster a regional green innovation atmosphere, so as to guide firms to actively allocate patent pledge funds toward environmentally friendly and low-carbon transformation. For regions lagging in digital infrastructure, governments should prioritize investment in 5G, big data, and artificial intelligence facilities to reduce corporate digital transformation costs and improve the operational efficiency of digital–green technology integration.

Furthermore, local governments should establish a systematic performance evaluation mechanism to quantitatively assess the effectiveness of green popularization campaigns and digital infrastructure development. By dynamically monitoring regional patent pledge financing scale, patent green-digital transformation efficiency, and corporate DGST performance, policymakers can accurately identify regional shortcomings, optimize the allocation of policy and financial resources, and effectively amplify the enabling effect of patent pledge financing on balanced and high-quality digital–green sustainable development.

Improve the quality and effectiveness of patent pledge financing to maximize its contribution to DGST. Given the negative moderating role of debt default risk, policymakers should strengthen risk-sharing and risk-monitoring mechanisms for patent pledge financing. Financial institutions may adopt differentiated credit assessment frameworks that consider both firms' debt risk and the quality of pledged patents, whereas governments can provide targeted guarantee support for firms with sound innovation potential but limited financing capacity.

In addition, greater attention should be paid to the technological value of pledged patents. Since both digital patent pledges and green patent pledges are found to promote DGST, governments should encourage firms to activate digital and green patent assets through dedicated financing programs and supportive intellectual property policies. Moreover, as only invention patent pledges exhibit a significant transformation effect, patent valuation and financing systems should place greater emphasis on high-value invention patents, thereby directing financial resources toward technologically advanced innovations with stronger transformation potential.

Finally, regulators should further strengthen the supervision of patent pledge activities and improve information disclosure mechanisms to ensure that financing support is linked to effective and enforceable pledge contracts. The insignificant effect of cancelled patent pledges suggests that only actual financing obtained through valid pledge arrangements can facilitate DGST, highlighting the importance of improving the quality and credibility of patent pledge financing markets.

5.3 | Limitations

1. Because of data availability constraints, although this study measures firms' DGST using information from corporate annual reports, relying solely on annual report disclosures may overestimate firms' actual transformation levels. Future research could expand the measurement of DGST by incorporating indicators based on firms' actual digital and green technology applications, thereby providing a more accurate assessment of firms' digital–green transformation processes.
2. Because of data availability constraints, patent pledge financing is measured only by the number of pledged patents. Although distinguishing among invention, utility model, and design patents partially captures differences in financing value, the actual amount of financing obtained through patent pledges cannot be accurately observed. Future research could employ more detailed data on patent pledge financing amounts to provide a more precise assessment of firms' financing activities.
3. This study does not systematically examine the boundary conditions under which patent pledge financing affects DGST. Factors such as firms' intellectual property endowments may influence the effectiveness of patent pledge financing. Future studies could further explore these moderating factors and conduct more comprehensive heterogeneity analyses.

Author Contributions

An Pan: conceptualization, methodology, investigation, validation, funding acquisition, writing – original draft, project administration, writing – review and editing, data curation, supervision, resources. **Puyu Mi:** conceptualization, investigation, writing – original draft, writing – review and editing, methodology, validation, data curation, software, formal analysis. **Yijiao Shi:** investigation, writing – review and editing, writing – original draft, validation, methodology, formal analysis, data curation. **Xunpeng Shi:** conceptualization, writing – original draft, writing – review and editing, supervision, validation.

Acknowledgments

This research was financially supported by the National Natural Science Foundation of China (Grant No. 72174056) and the Fundamental Research Funds for the Central Universities of Zhongnan University of Economics and Law (Grant No. 2722025DL007). Open access publishing facilitated by University of Technology Sydney, as part of the

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Funding

This work was supported by the National Natural Science Foundation of China (72174056) and the Fundamental Research Funds for the Central Universities of Zhongnan University of Economics and Law (2722025DL007).

Conflicts of Interest

The authors declare no conflicts of interest.

Endnotes

[1] Abnormal listing status refers to firms with ST or *ST warnings, trading suspension, or delisting arrangements. Following common practice in the literature, such firms are excluded to avoid bias.

[2] Coordination, coordination_w1, coordination_w2, and coupling all fall within the theoretical interval of 0–1 with consistent sample observations, presenting minor discrepancies in central tendency and volatility yet yielding consistent regression results to confirm the robustness of our baseline findings.

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