



# Digital Transformation and Green Innovation: The Roles of ESG Performance and R&D Intensity

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**Abstract.** As the digital economy continues to evolve alongside China's "dual-carbon" agenda, digital transformation has gradually emerged as a fundamental catalyst for enhancing firms' green innovation activities. Based on Chinese A-share listed firms over 2010–2023, this study constructs a regional digitalization index using data on commercial bank digital transformation and evaluates its impact on green innovation. Empirical results indicate a significant positive effect that is robust to multiple specifications. Mechanism analysis shows that this effect is driven by improvements in ESG performance and increased R&D investment. The impact is more pronounced among state-owned enterprises, non-manufacturing firms, and heavily polluting industries, suggesting that firm characteristics and regulatory environments matter. This study thus provides micro-level evidence on the role of digitalization in promoting corporate green transformation.

**Keywords:** Digital transformation; Green innovation; ESG performance; R&D intensity

## 1 Introduction

Firms, as major sources of resource consumption and environmental pressure, are central to green transformation and sustainable development. Green innovation, which combines economic and environmental benefits, has become an important means of addressing resource and ecological constraints. However, its high investment requirements, long development cycles, and substantial uncertainty often lead to financing constraints and insufficient incentives for firms.

At the same time, the rapid advancement of digital technologies has reshaped regional digital infrastructure and financial systems, thereby influencing firms' resource allocation and innovation environments. In this context, whether regional digitalization can effectively promote corporate green innovation remains an important question.

The existing literature provides mixed evidence. The promotion view suggests that digitalization alleviates financing constraints and improves resource allocation efficiency, thereby fostering green innovation [1], whereas the inhibition view argues that it may exacerbate resource misallocation under imperfect institutional conditions [2]. Overall, the evidence remains inconclusive.

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T. G. Guan et al. (eds.), *Proceedings of the 2026 4th International Conference on Digital Economy and Management Science (CDEMS 2026)*, Advances in Economics, Business and Management Research 392, [https://doi.org/10.2991/978-94-6239-699-9\\_28](https://doi.org/10.2991/978-94-6239-699-9_28)

Prior research predominantly captures regional digitalization using macro-level indicators. Khera (2021) proposes a digital financial inclusion index [3], while Wangs (2024) constructs composite measures based on digital infrastructure and application dimensions [4]. However, these approaches largely overlook the financial supply-side dimension of digitalization.

Based on this, two research gaps remain. First, existing measures pay limited attention to the role of financial supply in regional digitalization. Second, prior studies lack an integrated framework that jointly considers environmental performance and innovation investment.

Using a sample of Chinese A-share listed firms from 2010 to 2023, we construct a city-level digitalization index derived from commercial bank digital transformation. The empirical analysis adopts a two-way fixed effects framework to evaluate its effect on green innovation and to examine the mediating roles of ESG performance and R&D intensity.

This study contributes in three aspects. First, it develops a measure of regional digitalization from a financial supply-side perspective. Second, it identifies ESG performance and R&D intensity as key transmission channels. Third, it provides micro-level evidence based on green invention patents and highlights heterogeneous effects across ownership and industry characteristics.

## 2 Theoretical Analysis

### 2.1 The Impact of Regional Digitalization on Green Innovation

Regional digitalization promotes corporate green innovation through multiple channels. By improving digital infrastructure and data markets, firms gain broader access to strategic resources, which enhances the efficiency of resource allocation [5]. Moreover, enhanced information transparency reduces financing frictions and strengthens external monitoring, thereby improving firms' innovation incentives [6]. In addition, digitalization facilitates knowledge diffusion and technological spillovers, lowering innovation costs and supporting continuous green innovation [7].

Based on the above, we propose the following hypothesis:

H1: Regional digitalization significantly promotes corporate green innovation.

### 2.2 The Mechanisms of Regional Digitalization and Green Innovation

Building on the two-step analytical framework [8], the mediating roles of ESG performance and R&D intensity are examined. These two variables respectively reflect firms' sustainability performance and the level of innovation investment, capturing the key channels through which regional digitalization influences green innovation.

**The Mediating Role of ESG Performance.** Drawing on stakeholder and signaling theories, regional digitalization enhances information transparency and disclosure quality, thereby improving ESG performance and strengthening firms' credibility in capital

markets. Improved ESG performance further alleviates financing constraints and enhances firms' incentives for green innovation. Accordingly, regional digitalization promotes green innovation through ESG performance.

H2: ESG performance mediates the relationship between regional digitalization and corporate green innovation.

**The Mediating Role of R&D Intensity.** From the perspectives of resource allocation and endogenous growth, digitalization facilitates financing access and optimizes R&D resource allocation by alleviating information frictions. Increased R&D investment, as a key driver of innovation output, further strengthens firms' green innovation capacity. Accordingly, regional digitalization promotes green innovation through R&D intensity.

H3: R&D intensity mediates the relationship between regional digitalization and corporate green innovation.

### 3 Research Design

#### 3.1 Data Sources and Sample Selection

This study uses Chinese A-share listed firms from 2010 to 2023. Green patent data are sourced from CNRDS. A city-level digitalization index is developed based on commercial bank digital transformation, covering 293 prefecture-level cities, with data from the China City Statistical Yearbook and the Peking University Digital Transformation Index. The sample excludes financial firms, highly leveraged firms ( $Lev > 1$ ), ST/\*ST firms, and observations with missing key variables.

#### 3.2 Variable Definitions

**Dependent Variable: Corporate Green Innovation (Green\_Inv).** This study measures green innovation by green patent output, emphasizing invention patents given their higher technological content and stricter examination criteria. The main dependent variable (Green\_Inv) is the number of green invention patent applications. Green patents are identified using the IPC Green Inventory provided by WIPO, which categorizes environmentally relevant technologies based on IPC classifications.

**Independent Variable: Regional Digital Transformation Index (Digit).** This study constructs a city-level digitalization index by combining bank branch concentration with banks' digital transformation levels. Specifically, branch concentration is measured as the share of a single bank's branches in total local branches. Since less developed regions are often dominated by a few large state-owned banks with relatively high digitalization levels, directly using this measure may lead to upward bias. To address this issue, the reciprocal of branch concentration is interacted with each bank's digital transformation index and then aggregated across banks to obtain a composite regional digitalization indicator. The digital intangible assets of listed firms within the same re-

gion are aggregated by location of registration, yielding a regional measure of enterprise digital assets. This measure reflects regional digital finance and information infrastructure from a financial supply-side perspective and exhibits relatively strong exogeneity, helping to mitigate potential reverse causality.

### Mediating variables.

*ESG Performance (ESG\_score).* ESG performance (ESG\_score) is measured using the comprehensive ESG score provided by Huazheng Index, ranging from 0 to 100, with higher values indicating better performance.

*Research and Development Intensity (RD).* R&D intensity (RD) is measured as the share of R&D expenditure in operating revenue and reflects the proportion of firm resources allocated to innovation activities.

**Control Variables.** Firm-level controls are included to account for observable characteristics, including firm size (Size), listing age (ListAge), leverage (Lev), Tobin's Q (TobinQ), managerial ownership (Mshare), and market competition (HHI) [9], with reference to Zhang et al. (2024).

### 3.3 Model Specification

To examine the impact of regional digital transformation on corporate green innovation, this study specifies the following econometric model:

$$\text{Green\_Inv}_{i,t} = \alpha + \beta \text{Digit}_{m,t-1} + \gamma \text{Controls}_{i,t-1} + \delta_i + \phi_t + \varepsilon_{i,t} \quad (1)$$

$\text{Green\_Inv}_{i,t}$  captures firm  $i$ 's green innovation level in year  $t$ .  $\text{Digit}_{m,t-1}$  represents the regional digital transformation index of prefecture-level city  $m$  where the firm is located in year  $t-1$ . In the empirical analysis, the original weighted index is scaled by dividing it by 10,000.  $\text{Controls}$  denotes a set of firm-level control variables.  $\delta_i$  and  $\phi_t$  represent firm fixed effects and year fixed effects, respectively, and  $\varepsilon_{i,t}$  is the error term.

The coefficient  $\beta$  captures the impact of regional digital transformation on corporate green innovation. A significantly positive  $\beta$  provides support for Hypothesis H1.

### 3.4 Descriptive Statistics

Table 1 presents summary statistics. Green innovation exhibits a right-skewed distribution, indicating substantial heterogeneity across firms. The digitalization index also shows significant regional disparities. Overall, the variables fall within reasonable ranges, supporting the validity of the empirical analysis.

**Table 1.** Descriptive Statistics

Variable	(1) N	(2) Mean	(3) Std.Dev	(4) Min	(5) Median	(6) Max
Green_Inv	44898	4.606	29.31	0	0	1335
Digit	40573	243.4	423.5	0.0960	61.97	1651
Size	44898	22.17	1.338	14.94	21.97	28.70
Lev	44898	0.413	0.209	0.00708	0.403	0.998
TobinQ	44885	2.103	4.155	0.611	1.599	715.9
ListAge	44898	2.005	0.966	0	2.197	3.526
HHI	44898	0.0898	0.107	0.0130	0.0611	1.000
Mshare	43661	0.149	0.204	0	0.0151	0.900

## 4 Empirical Results

### 4.1 Baseline Results

Table 2 reports baseline results. Column (2), which includes firm and year fixed effects with firm-clustered standard errors, shows a positive and significant coefficient on Digit (0.007), supporting H1.

**Table 2.** Baseline and Robustness Regression Results

Variable	(1) Without Con- trols	(2) With Controls	(3) Excluding High-Tech Firms	(4) Alternative De- pendent Variable
	Green Inv	Green Inv	Green Inv	Green Inv Grant
Digit	0.009*** (3.41)	0.007*** (3.10)	0.0024*** (0.0008)	0.0029** (0.0013)
Observations	40573	39411	15,640	39,411
Year FE	YES	YES	YES	YES
Firm FE	YES	YES	YES	YES
R-squared	0.036	0.043	0.0754	0.0278
Number of Stkcd	4,695	4,695	1,899	4,869

t statistics in parentheses, Robust standard errors in parentheses

\* p < 0.1, \*\* p < 0.05, \*\*\* p < 0.01

### 4.2 Robustness Tests

**Excluding High-Tech Firms.** Excluding high-tech firms to alleviate sample selection concerns yields consistent results, with Digit remaining positive and significant at the 1% level in Column (3) of Table 2, reinforcing the robustness of the baseline estimates.

**Alternative Dependent Variable.** The dependent variable is replaced with the number of granted green invention patents (Green\_Inv\_Grant). Consistent results are obtained in Column (4), where Digit remains positive and significant, confirming robustness under alternative measures.

### 4.3 Endogeneity Test

**Instrumental Variable Approach (IV-2SLS).** An instrumental variable approach is employed to alleviate endogeneity concerns, where mobile phone penetration (Mobile) is used as the instrument. In Table 3, the first-stage results show that Mobile is strongly correlated with Digit, with an F-statistic above 10, indicating sufficient instrument relevance. The second-stage estimates confirm that Digit remains significantly positive, with a larger coefficient than in the baseline specification, suggesting that the baseline results may underestimate the effect.

**Controlling for Industry Fixed Effects.** Including industry fixed effects does not alter the results, as the coefficient on Digit in Table 3 remains positive and significant at the 1% level, suggesting that the findings are not explained by industry-specific factors.

**Table 3.** Endogeneity Test

Variable	(1)	(2)	(3)
	1st-Stage Digit	2st-Stage Green_Inv	Industry FE Green_Inv
Digit		0.006*** (3.03)	0.0073*** (0.0024)
Mobile	76.435*** (17.42)		
Observations	39,367	39,367	39,411
R-squared	0.339	0.144	0.0472
Number of Stkcd	4,865	4,865	4,865
Year FE	YES	YES	YES
Firm FE	YES	YES	YES

## 5 Further Analysis

### 5.1 Mechanism Analysis

This study adopts the two-step approach [8] to examine the mediating roles of ESG performance and R&D intensity.

**ESG Performance.** Estimation based on Equation (2) captures the effect of digital transformation on ESG scores, whereas Equation (3) is applied to assess the role of ESG scores in driving green innovation.

$$ESG\_score_{i,t} = \alpha + \beta Digit_{m,t-1} + \gamma Controls_{i,t-1} + \delta_i + \phi_t + \varepsilon_{i,t} \quad (2)$$

$$Green\_Inv_{i,t} = \alpha + \beta ESG\_score_{i,t} + \gamma Controls_{i,t} + \delta_i + \phi_t + \varepsilon_{i,t} \quad (3)$$

Digitalization significantly improves ESG performance, as reflected by the coefficient of Digit in Column (1) of Table 4 (0.0008\*\*\*). In turn, ESG performance promotes green innovation, with ESG\_score remaining positive and significant in Column (2) (0.0693\*\*\*). This finding implies that improved ESG performance helps ease financing constraints and strengthens firms' innovation incentives. Overall, the evidence supports the mediating role of ESG performance, confirming Hypothesis H2.

**R&D Intensity.** Estimation based on Equation (4) captures the effect of digital transformation on R&D intensity, whereas Equation (5) is applied to assess the role of R&D intensity in driving green innovation.

$$RD_{i,t} = \alpha + \beta Digit_{m,t-1} + \gamma Controls_{i,t-1} + \delta_i + \phi_t + \varepsilon_{i,t} \quad (4)$$

$$Green\_Inv_{i,t} = \alpha + \beta RD_{i,t} + \gamma Controls_{i,t-1} + \delta_i + \phi_t + \varepsilon_{i,t} \quad (5)$$

The results indicate that digitalization significantly enhances R&D intensity, with the coefficient of Digit on RD being 81.6533\*\*\* in Column (3) of Table 4. R&D intensity, in turn, positively influences green innovation, as reflected by the coefficient of RD (0.0662\*\*\*) in Column (4). Digitalization enhances corporate green innovation by stimulating R&D investment, which is consistent with Hypothesis H3.

**Table 4.** Mechanism Analysis Results

Variable	(1) ESG_score	(2) Green Inv	(3) RD	(4) Green Inv
Digit	0.0008*** (0.0002)		81.6533*** (29.7434)	
ESG_score		0.0693*** (0.0136)		
RD				0.0662*** (0.0202)
Observations	37,654	46,701	12,622	40,430
R-squared	0.0542	0.1035	0.0974	0.0930
Firm FE	YES	YES	YES	YES
Year FE	YES	YES	YES	YES
Number of Stked	4,695	5,273	2,474	5,194

## 5.2 Heterogeneity Analysis

To examine heterogeneity, the sample is partitioned by ownership structure, industry type, and environmental regulation intensity. The results in Table 5 indicate that the effect of regional digitalization is more pronounced in state-owned enterprises, non-manufacturing firms, and heavily polluting industries. This pattern suggests that firms with stronger policy support or higher regulatory pressure are more responsive to improvements in the digital environment.

**Table 5.** Heterogeneity Analysis Results

	(1)	(2)	(3)	(4)	(5)	(6)
	SOEs	Non-SOEs	Manufacturing	Non-Manufacturing	Heavily Polluting	Non-Heavily Polluting
Variable	Green_Inv	Green_Inv	Green_Inv	Green_Inv	Green_Inv	Green_Inv
Digit	0.0175***	-0.0011*	0.0018**	0.0023**	0.004**	0.002**
	(0.0050)	(0.0007)	(0.0009)	(0.0009)	(0.002)	(0.001)
Observations	12,954	26,457	25385	14026	8125	31286
Firm FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES
Number of			4,869	4,869		
Stkcd	4,869	4,869			4,869	4,869
R-squared	0.0675	0.0435	0.1217	0.0855	0.09	0.11

## 6 Discussion and Conclusion

Empirical evidence from Chinese A-share listed firms over 2010–2023 indicates that regional digitalization plays a significant role in promoting corporate green innovation, with robust results across model specifications. The underlying mechanism reflects improvements in ESG performance and greater R&D investment. The effect is more pronounced in state-owned enterprises, non-manufacturing sectors, and heavily polluting industries, highlighting the role of firm characteristics and regulatory pressures.

These findings support the promotion view of digitalization and highlight its role in simultaneously enhancing sustainability performance and innovation investment. In terms of policy implications, governments should strengthen digital infrastructure and digital financial systems, while firms should leverage digital technologies to improve ESG practices and R&D investment. In addition, differentiated policies are needed to support non-state-owned enterprises and enhance digital governance in heavily polluting industries.

However, there are still limitations. The sample is limited to Chinese A-share listed firms, and potential nonlinear and dynamic effects are not fully explored. Future research could extend the analysis to cross-country settings and longer time horizons.

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