

The Moderating Role of VC/PE Ownership in the Relationship Between Digital Transformation and Corporate Green Innovation Quality: Evidence from Chinese Listed Firms

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ABSTRACT

This essay examines the ability of digital transformation to generate valuable green innovation outcomes and whether VC/PE ownership moderates this relationship. In addition, this study's sample covers Chinese listed firms from 2017 to 2024 to measure green innovation quality by green patent citations and identifies VC/PE ownership based on Orbis shareholder ownership data. Furthermore, the empirical results show that green innovation quality is significantly improved by digital transformation, while the direct effect of VC/PE ownership is not significant. More importantly, VC/PE ownership negatively moderated the conversion of digital transformation capabilities into green innovation outputs, suggesting that higher VC/PE ownership may weaken the value of digitalization for green innovation quality. Moreover, this essay adds to the existing literature by shifting attention from green innovation quantity to quality. Also, it shows that external ownership participation may shape how digital capabilities are converted into high-quality green innovation outcomes.

Keywords: Digital Transformation; VC/PE ownership; Moderating Effect; Corporate Green Innovation Quality; Chinese Listed Companies

1. INTRODUCTION

1.1 Research Background and Problem

In recent years, green innovation has gradually become an important path for enterprises to respond to environmental pressure while maintaining sustainable development and long-term competitive. However, simply counting green patent may not fully reflect the real value of corporate green innovation. That is because patent quantity cannot show whether the innovation has strong technological influence or knowledge diffusion value. Therefore, recent studies have paid more attention to green innovation quality, which better captures the technological value, practical significance and long-term competitiveness of green innovation outcomes [2,4].

At the same time, digital transformation is reshaping firms' information processing, resource allocation and innovation activities. Prior studies show that digital transformation can improve capital market information environment, enhance resource allocation efficiency and promote green innovation [6-8]. Hence, digital transformation may provide an important internal capability for improving corporate green innovation quality.

Simultaneously, green innovation usually requires large investment, long R&D cycles and uncertain returns. This means that external capital and governance support may also influence firms' green innovation decisions. VC/PE ownership, as an external ownership characteristic, may provide capital support, governance monitoring and resource networks. However, existing studies often examine digital transformation and external equity investment separately, and relatively limited attention has been paid to whether VC/PE ownership changes the effect of digital transformation on green innovation quality. Based on this gap, this study examines how digital transformation affects corporate green innovation quality and whether VC/PE ownership moderates this link in Chinese listed firms.

1.2 Research Significance and Hypotheses

This study has both theoretical and practical significance. Theoretically, it incorporates digital transformation, VC/PE ownership and green innovation quality into one analytical framework. This framework helps explain whether digital transformation improves green innovation quality, and also helps to identify under what ownership conditions this impact may be stronger or weaker. In practice, the findings can help firms understand the value of digital transformation, and

guide VC/PE institutions to balance financial performance with long-term green innovation. At the policy level, this study can also provide evidence for the formulation of policies that connect digital infrastructure, green finance, and innovative investments. Based on the above analysis, this essay focuses on the following research question:

RQ1: Is VC/PE ownership directly associated with corporate green innovation quality?

In addition, this study further investigates whether digital transformation improves corporate green innovation quality and whether VC/PE ownership moderates this relationship. These issues are further developed into hypotheses in the theoretical analysis section.

2. LITERATURE REVIEW

2.1 Green Innovation Quality

Green innovation refers to innovation in products, processes, management or institutions that reduces resource consumption, lowers pollution emissions and improves environmental performance. Cheng et al. ^[2] point out that different types of green innovation may have different implications for companies' future environmental and financial performance. Also, D. Zhang et al. ^[10] suggest that green innovation can generate economic value. These studies support the view that green innovation quality should be emphasized.

Patent counts alone may not fully capture the technological content and practical value of green innovation outcomes. By contrast, green patent citations can better reflect technological influence and knowledge diffusion. Therefore, using the number of green patent citations as a proxy variable for the corporate green innovation quality can make this study more directly to measure the value and the impact of green innovation achievements. In this way, this study focuses on whether firms are capable of producing high-quality green innovation outcomes rather than merely conducting green innovation activities.

2.2 Digital Transformation and Green Innovation Quality

Digital transformation has become a key path for firms to improve efficiency and innovation capability. The reason is that digital technologies can help business collect, process, and use information more efficiently, which matches the characteristics of green innovation projects, such as long-term commitment and ongoing oversight. This logic is also supported by prior studies. Li and Zhang ^[7] show that digital transformation can improve the information environment of capital markets, while Jiang and Li ^[6] find that it enhances resource allocation efficiency and productivity. In the green innovation field, Wang and Zhong ^[8] provide firm-level evidence from China that digital transformation is positively related to green innovation. Zhang et al. ^[11] further connect digital transformation, financing modes and green innovation within an integrated framework.

Overall, the literature supports the positive role of digital transformation in green innovation. However, existing studies mainly investigate the direct effect of digital transformation on green innovation, with limited attention to the moderating role of external ownership. This creates room for examining VC/PE ownership as a moderating variable.

2.3 VC/PE Ownership and Innovation

Prior studies on venture capital and private equity show that external equity investors may influence corporate innovation through financing support, governance participation and resource networks. This is particularly important for the green innovation quality because external equity investors can drive companies to concentrate on more valuable and impactful green technologies rather than simply increasing the number of green patents. According to Arqué-Castells ^[1], venture capital can stimulate patent activity, while Dimitrova and Eswar ^[3] find that venture capital incentives may affect both patent quantity and quality. Moreover, González-Urbe ^[5] documents active innovation resource exchange within venture capital portfolios.

These findings indicate that external equity investors can shape firms' innovation activities beyond simple financial support. Through governance engagement, VC/PE investors are able to push enterprises to choose innovative projects with more long-term value. Building on this logic, the discussion can be extended to green innovation quality. Dong et al. ^[4] and Yang et al. ^[9] suggest that venture capital can affect green innovation outcomes. Although these studies mainly focus on venture capital rather than the VC/PE ownership measure used in this study, they provide a theoretical foundation for examining how external ownership characteristics may relate to green innovation quality and moderate the role of digital transformation.

2.4 Literature Summary and Research Gap

A review of the literature suggests three research gaps. Firstly, green innovation research has gradually shifted from quantity to quality, but the formation mechanism of high-quality green innovation remains insufficiently explained. This gap is critical because green patents numbers cannot fully reflect whether a company has produced influential and valuable green technologies. Secondly, digital transformation research has demonstrated its positive role in information environment and resource allocation, but it rarely examines whether external ownership characteristics shape this effect. Thirdly, despite evidence on venture capital and innovation, whether VC/PE ownership directly relates to green innovation quality and whether it moderates the relationship between digital transformation and green innovation quality remain underexplored. By introducing VC/PE ownership into digital transformation and green innovation framework, this research links internal digital capability with external ownership support. In the following sections, this study will solve these gaps using enterprise-level evidence from Chinese listed firms from 2017 to 2024.

3. THEORETICAL ANALYSIS AND RESEARCH HYPOTHESES

3.1 Digital Transformation and Green Innovation Quality

Following prior evidence on digitalization and green innovation, this section discusses why digital transformation may improve green innovation quality. Digital transformation may work through three channels. First, it improves the corporate information environment, which allows firms to detect potential green innovation opportunities and maintain long-term green R&D activities. Second, digital capabilities support more efficient resource allocation, allowing capital, labor and knowledge resources to be directed toward innovation activities. Third, it supports collaboration and knowledge integration, which facilitates firms transform green R&D inputs into high-quality innovation outcomes. Based on these mechanisms, this study proposes H1.

3.2 The Moderating Role of VC/PE Ownership

VC/PE ownership may shape how digital transformation contributes to green innovation quality. From the one perspective, VC/PE investors may provide capital, governance monitoring and resource networks that support innovation activities. From the other perspective, green innovation quality usually depends on long-term technological accumulation and uncertain returns. If VC/PE shareholders place stronger emphasis on short-term performance, corporation may allocate digital resources to commercially visible projects rather than long-term green R&D.

Thus, VC/PE ownership may not automatically strengthen the positive effect of digital transformation. Instead, it may change the direction and intensity of this relationship. Following this line, this study has two main objectives. First, it explores the direct association between VC/PE ownership and high-quality green innovation. Second, it analyzes the conditional role of VC/PE ownership in the pathway from digital transformation to green innovation quality.

3.3 Research Hypotheses

Following the theoretical analysis, the hypotheses are developed as follows:

H1: Digital transformation significantly improves corporate green innovation quality.

H2: VC/PE ownership moderates the relationship between digital transformation and corporate green innovation quality.

The direct effect of VC/PE ownership on green innovation quality is not stated as a directional hypothesis because its role may be conditional.

4. METHODOLOGY

4.1 Sample and Data Sources

The research sample consists of Chinese listed firms observed from 2017 to 2024. Meanwhile, non-financial listed firms are retained, while ST firms, firms with severe missing key variables, abnormal business conditions and obvious outliers are excluded. To reduce the influence of extreme values, all continuous variables are adjusted through using 1% and 99% winsorization.

Financial statement variables, governance variables and basic firm information are mainly derived from CSMAR. Besides, green innovation quality is proxies by the annual green patent citation data from CSMAR. Additionally, digital transformation is measured by CSMAR digital transformation indicators of Chinese listed firms. In addition, VC/PE

ownership is constructed from the latest available Orbis shareholder ownership information by identifying VC/PE-type shareholders and calculating their total ownership share. Since this ownership data reflects the latest available shareholder structure, it is treated as a enterprise-level ownership characteristic rather than a yearly VC/PE entry event.

4.2 Variable Measurement

Table 1 summarizes the definitions of the main variables. Green innovation quality is measured by $\ln(1 + \text{citations received by green patents})$, which captures the technological impact and knowledge diffusion value of green innovation outcomes. To examine its determinants, this study uses digital transformation as the core independent variable and VC/PE ownership share as the main moderating variable. In the robustness tests, a VC/PE ownership dummy is further used as an alternative measure of external ownership participation.

Table 1. Variable Definition

Variable Type	Variable Name	Symbol	Measurement
Dependent Variable	Green Innovation Quality	GIQ	$\ln(1 + \text{citations received by green patents})$
Alternative Dependent Variable	Green Invention Patent Grants	Green inv. grant.	$\ln(1 + \text{number of authorized green invention patents})$
Independent Variable	Digital Transformation	DT	Digital transformation indicator of Chinese listed firms from CSMAR
Moderating Variable	VC/PE Ownership Share	VC share	Total shareholding ratio held by VC/PE-type shareholders identified from Orbis ownership data
Supplementary VC/PE Variable	VC/PE Ownership Dummy	VC	1 if the firm has VC/PE-type shareholders, otherwise 0
Interaction Term	VC/PE Ownership x Digital Transformation	VC share X DT	VC share x DT
Alternative Interaction Term	VC/PE Dummy x Digital Transformation	VC X DT	VC x DT
Controls	Firm-level controls	Controls	Size, leverage, ROA, cash flow, growth, intangible asset ratio, firm age, listed age, manager number and independent directors
Fixed Effects	Industry and Year Fixed Effects	Industry FE, Year FE	Included
Standard Errors	Clustered Standard Errors	Clustered SE	Clustered at firm level

4.3 Model Specification

To test H1, this study specifies the following baseline model:

$$GIQ_{it} = \alpha_0 + \alpha_1 DT_{it} + \alpha_2 Controls_{it} + Industry_i + Year_t + \varepsilon_{it} \quad (1)$$

Among them, GIQ_{it} denotes green innovation quality for $Firms_i$ in $Year_t$; DT_{it} demonstrates digital transformation level; $Controls_{it}$ symbolizes a set of firm-level control variables, and $Industry_i$ represents industry fixed effects, and $Year_t$ represents year fixed effects. If α_1 is positive and significant, H1 is supported.

To test H2, this study incorporates VC/PE ownership and its interaction term with digital transformation into the model:

$$GIQ_{it} = \beta_0 + \beta_1 DT_{it} + \beta_2 VC\ share_i + \beta_3 (VC\ share_i \times DT_{it}) + \beta_4 Controls_{it} + Industry_i + Year_t + \varepsilon_{it} \quad (2)$$

Among them, $VC\ share_i$ represents the total ownership share held by VC/PE-type shareholders. The interaction term $VC\ share_i \times DT_{it}$ is used to test whether the effect of digital transformation on green innovation quality varies with VC/PE ownership. If β_3 is significant, it indicates that VC/PE ownership has a moderating effect. If β_3 is negative and

significant, it suggests that higher VC/PE ownership reduces the positive link between digital capabilities and green innovation quality.

4.4 Robustness Tests

This study conducts three robustness tests:

The first one is that using green invention patent grants as an alternative dependent variable. The second one is that replacing VC/PE ownership share with a VC/PE ownership dummy. The third one is that re-estimating the model using the 2017-2023 subsample. These tests examine whether the main findings remain consistent under alternative measurements and sample periods.

5. EMPIRICAL RESULTS

5.1 Descriptive Statistics

Table 2 presents an overview of the distribution of the main variables. The dependent variable is the quality of green innovation, calculated as the natural logarithm of one plus the number of green patent citations. The table also reports the distribution of digital transformation, VC/PE ownership, interaction terms, and firm-level control variables.

Table 2. Descriptive Statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
GIQ	23607	0.837	1.302	0	8.470
Green citation	23607	12.788	109.744	0	4768
DT	16827	0.129	0.116	0.003	4.062
VC share	23607	1.487	11.363	0	100
VC	23607	0.022	0.146	0	1
VC share X DT	16827	0.172	1.698	0	47.483
Size	23607	22.082	1.195	19.025	28.360
Lev	23607	0.368	0.188	0.014	3.513
ROA	22545	0.040	0.078	-1.919	0.786
Cashflow ratio	22545	0.052	0.070	-0.647	0.839
Growth	18802	0.249	8.566	-0.985	944.100
Intangible ratio	23568	0.040	0.035	0.000	0.508
Firm age	23607	3.021	0.297	1.386	4.234
Listed age	23607	1.876	0.962	0	3.555
Manager num	23573	6.299	2.510	1	25
Indep num	23573	3.042	0.496	0	9

5.2 Regression Results

Table 3 summarizes the baseline regression estimates and robustness test results. In Model (1), the estimated coefficient on digital transformation is positive and significant, which is consistent with H1. The coefficient of VC/PE ownership share is not significant, suggesting that VC/PE ownership does not show a clear direct effect on green innovation quality. In addition, a significantly negative coefficient is observed for the interaction term of VC/PE ownership share and digital transformation, indicating that VC/PE ownership moderates the effect of digital transformation on green innovation quality. Therefore, H2 is supported in terms of the existence of a moderating effect, although the direction is negative.

Table 3. Baseline and Robustness Regression Results

Variable	(1) GIQ	(2) Alt DV	(3) Alt VC	(4) 2017-2023
VC share	0.00203 (0.00169)	0.00000449 (0.00104)		0.00151 (0.00197)
DT	0.677*** (0.184)	0.282*** (0.0994)	0.680*** (0.185)	0.714*** (0.198)
VC share X DT	-0.0360*** (0.0125)	-0.00771 (0.00724)		-0.0351** (0.0141)
VC			0.119 (0.172)	
VC X DT			-1.303 (1.111)	
Controls	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	13,632	13,632	13,632	11,576
Adjusted R-squared	0.443	0.341	0.442	0.450

Notes: Robust standard errors are used in the regression. They are clustered at the firm level and reported in parentheses. Industry and year fixed effects are included across all specifications. Statistical significance at the 10%, 5%, and 1% levels is indicated by *, **, and ***, respectively.

6. DISCUSSION

6.1 Explanation of the Negative Moderating Effect

The negative moderating effect may be explained by the time horizon and performance orientation of VC/PE shareholders. The reason is that digital transformation improves information transparency and makes innovation activities more observable. When VC/PE ownership share is higher, firms may face stronger pressure to allocate digital resources to projects with clearer short-term outcomes, such as operational efficiency, cost control or commercially visible innovation. However, high-quality green innovation usually depends on long-term technological accumulation and uncertain returns. As a result, this short-term pressure may weaken the transformation of digital capabilities into high-quality green innovation outcomes.

6.2 Implications

From theoretical perspective, this study contributes to the literature in two main ways. First, it focuses on green innovation quality rather than only green innovation quantity, highlighting the technological influence and long-term value of green innovation outcomes. Second, it shows that digital transformation is an important internal driver of high-quality green innovation. In addition, this study extends the external ownership literature by showing that VC/PE ownership does not automatically promote green innovation and may even weaken the positive role of digital transformation under certain conditions.

From practical perspective, the findings provide implications for firms, VC/PE institutions and policymakers. In terms of firms, they should treat digital transformation as a strategic tool for improving green innovation quality and ensure that digital resources are directed toward long-term green R&D. For VC/PE institutions, they should balance financial performance with long-term green innovation value when participating in corporate governance. When it comes to policymakers, they should promote digital infrastructure while guiding external capital to support long-term green innovation rather than only short-term measurable outputs.

7. CONCLUSION

This study examines digital transformation, VC/PE ownership and corporate green innovation quality using Chinese listed firms from 2017 to 2024. The empirical evidence suggests that digital transformation contributes to higher green innovation quality. However, VC/PE ownership does not show a significant direct effect. The interaction between VC/PE ownership shares and digital transformation is significantly negative, suggesting that higher VC/PE ownership may weaken the positive effect of digital transformation. Robustness tests confirm the stable positive role of digital transformation, although the moderating effect of VC/PE ownership remains conditional.

This study has several limitations. VC/PE ownership is measured using the latest available Orbis shareholder ownership data, so it is treated as a firm-level ownership characteristic rather than a yearly VC/PE entry event. Potential endogeneity issues may also remain, although several robustness tests are conducted. Future research may use yearly ownership data, deal-level VC/PE investment data, lagged variables or instrumental variables to further examine dynamic and causal effects.

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