# Digital Transformation and Continuous Green Innovation of Enterprises: An Empirical Research based on Intermediaries and Regulation Mechanisms

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*Abstract:* - In the rapidly expanding realm of the digital economy, the pivotal role of digital transformation in propelling businesses towards sustainable and progressive development is becoming increasingly evident. Examining how digital transformation motivates firms to innovate in green management practices sustainably is essential. Utilizing a dataset encompassing Chinese A-share listed companies from 2008 to 2020, this study empirically examines digital transformation's effects on the ongoing quest for green innovation. Additionally, it delves into the mediating role that green management innovation plays in this dynamic and evaluates how the fit of the innovation ecosystem within a company's regional environment serves as a moderating factor. The findings indicate that digital transformation strengthens firms' capacities for persistent green innovation. Green management innovation is revealed to be an intermediary in this process; meanwhile, aligning the innovation ecosystem's niche within a company's region amplifies the influence of digital transformation on fostering sustainable green innovation. This research offers valuable theoretical perspectives for organizations that leverage digital transformation as a strategic asset for ecologically friendly manufacturing and long-term expansion. This research examines how digital transformation drives sustainable green innovation in businesses, a significant but less-studied area. We aim to uncover the mechanisms influencing innovation, emphasizing the impact of green management and the fit of the innovation environment. We strive to provide empirical insights that enhance theoretical knowledge at the junction of digital strategy and environmental responsibility, guiding corporate practices toward operational efficiency and ecological sustainability. The study intends to foster a corporate ethos by integrating digital initiatives with green innovation and advancing global sustainable development.

*Key-Words:* - digital transformation; environmental innovation; green management innovation; intermediary mechanisms; continuous green innovation; innovation ecological niche suitability; ecosystem adaptability; resource-based perspective; dynamic capabilities.

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## 1 Introduction

As the world's economy grows swiftly and demands on resources and the environment escalate, the role of enterprises in environmental and social stewardship has gained prominence. The Chinese government has consistently highlighted the importance of fostering a market-based system for green technological innovation. Companies increasingly embrace strategies that prioritize green innovation as essential market participants. This shift towards green growth seeks to establish a harmonious balance between financial gains and environmental protection. Innovation is the cornerstone of progress, with green innovation being a crucial method for companies to harmonize industrial optimization and transformation, enhance energy efficiency, and minimize emissions during production. This approach addresses the dual objectives of securing economic achievements boo, sting environmental advantages, and strengthening companies' fundamental competitive edge, paving the way for sustainable, high-quality growth. This method is instrumental in activating the innovative spirit within companies, driving the continuous enhancement of economic returns, and ensuring sustainable progress towards high-quality development, [1], [2]. Furthermore, it represents a

vital strategy in invigorating the innovative dynamism of companies, fostering the perpetual increase of economic benefits, and realizing sustainable, superior-quality development, [3].

In the context of rapid worldwide economic growth and increasing demands on natural resources and the environment, the importance of companies in fulfilling their environmental and social responsibilities has grown more significant. As central agents in economic transactions, companies are increasingly adopting strategies incorporating green innovation. The pursuit of green progress by businesses aims to strike a fresh equilibrium between financial gains and ecological conservation. Innovation is the linchpin of growth, with green innovation as a critical tactic for businesses to fine-tune and remodel industrial frameworks, enhance energy conservation, and curtail emissions during the production cycle. Moreover, this is essential for maintaining growth while managing the twin objectives of economic achievement and environmental improvement. Further, it stands as a critical route for firms to fortify their foundational competitive strengths, attain eco-friendly growth, invigorate innovation momentum, foster the ongoing expansion of economic rewards, and secure high-caliber, enduring development, [1], [3].

The currently widely accepted definition of digital transformation is using emerging technologies to optimize business operations and models, enhance customer experience, and reshape organizational business models, strategic decision-making processes, and internal governance mechanisms, [4]. Digital transformation in enterprises is a continuous journey that fundamentally improves customer experience, business and operational processes, or organizational culture through digital technologies and strategies. The essence o is based on organizational-level changes: restructuring business models, cultivating employees' digital skills, and beginning a process of continuous experimentation and iteration, [5], applying digital capabilities to product development, business processes, and resource allocation, thereby reducing management risks brought by market turbulence, meeting customer needs, and enhancing industry competitiveness, [6]. Different sectors strive to adopt digital technologies, including mobile internet, social media, and intelligent embedded systems, to supersede conventional technologies such as ERP systems. Their goal is to enhance customer engagements, internal operations, and value generation by leveraging digital information technology for fundamental business enhancements, [7], [8], streamlining business practices, or establishing novel business models, [9], thus boosting organizational effectiveness and impact, [10], [11]. Green management innovation emphasizes that enterprises apply the ideas and methods of green quality management, [12], taking the coordinated and sustainable development of ecology and economy as strategic guidance, [13]. It involves implementing management concepts and processes such as environmental pollution prevention, resource recycling, green product development and design, and green consumption in various production and business activities, [14]. Green management innovation can enable enterprises to manage organizational resources more efficiently and intelligently, optimize production processes, improve resource utilization efficiency, and enhance the enterprise's capability for continuous green innovation.

The innovation ecosystem concept originated from ecosystem theory. Reference, [15], subsequently introduced this concept into organizational strategic management research. The essence of the innovation ecosystem is an aggregation and integration system of innovation resources based on innovation capabilities, mainly consisting of innovation entities, innovation resources, and the innovation environment. The ecological niche of the innovation system refers to the position established or occupied by innovation entities using innovation resources in a particular region within the innovation environment. The suitability of the ecological niche represents the closeness of the actual environmental conditions to the optimal environmental conditions, [16], reflecting the degree of match between the innovation resources needed by the innovation entities for innovation activities and the innovation resources they can obtain.

To some extent, it expresses the satisfaction level of innovation entities in getting innovation resources. Innovation entities enhance their innovation capabilities by sharing knowledge and information, coordinating and allocating innovation resources, and realizing resource exchange and application with the innovation environment through interaction and collaboration with other entities within the system. Innovation resources refer to various resources in the innovation ecosystem that support innovation entities in their innovation activities. An appropriate innovation environment can create a favorable space for innovation entities to carry out innovation activities. High suitability leads to better satisfaction of the innovation entities in obtaining the necessary

resources, and the higher the innovation vitality within the system is, the more conducive it is to drive innovation entities towards technological transformation and change.

While attention to green innovation in firms is increasing, more research is needed to explore it. It stands at the heart of digital progress and is the primary goal for businesses aiming to enhance the quality of their activities, [17]. It can optimize resource use efficiency, minimizing losses and excess in production and operational processes. Such optimization bolsters product efficiency spurs technological advancements to bolster core competitive edges, and elevates the organization's environmental performance. It mitigates the ecological and resource pressures associated with industrial progress, guiding a path toward eco-friendly and sustainable growth, [18]. With these considerations in mind, this study positions green managerial innovation as an intermediary factor and the fit of the innovation ecosystem as a conditional variable to investigate the dynamics between a company's digital shift and its ongoing green innovation efforts. The unique contribution of this research is the formulation of a mediating model linking "corporate digital change—green managerial innovation—ongoing green innovation" and adding an innovation ecosystem fit to create a moderating framework. This delves into the essential interactions between digital change and sustained green innovation in businesses, offering fresh perspectives on persistent green innovation pathways and providing theoretical and practical guidance for companies aiming for superior green growth.

This paper offers a structured exploration of the link between digital transformation and business green innovation. It begins with an introduction that underscores the importance of digital transformation for driving green innovation. The theoretical framework and literature review in Section 2 lay the groundwork for our empirical study. Section 3 outlines our methodology, detailing data selection, variable measurement, and regression model construction, ensuring research transparency and reproducibility. Section 4 presents empirical results, showing digital transformation's substantial effect on green innovation, influenced by green management innovation and the innovation ecological niche. Section 5 discusses these results, considering sustainable development and digital strategy, and contributes to the field. Section 6 concludes with implications for academia and industry, suggesting future research directions and emphasizing the role of digital transformation in sustainable innovation.

## 2 Theoretical Analysis and Research Hypotheses

Resource-based theory stands as a fundamental framework within management and organizational studies. It positions the business as the primary subject of scrutiny, emphasizing resource attributes as its core tenet. This theory articulates the intrinsic nature of companies and the processes by which they can secure enduring competitive edges, [19]. It sheds light on the circumstances that enable a firm's resources to become a foundation for competitive superiority, [20]. Diverging from earlier concepts prioritizing the scrutiny of external market conditions, the resource-based view concentrates on the internal assessment of resource variability among businesses or sectors, highlighting how these variances can evolve into lasting competitive strengths for firms, [21]. A company is considered to possess a competitive advantage when it can operate more cost-effectively and satisfy consumer demands more adeptly than its competitors, thereby attaining superior industry performance, [22]. From the resource-based theory perspective, as a continuous and complex technological activity, corporate green innovation requires a wealth of knowledge, skills, and resources to support it. The resource base of a single domain needs to be increased to meet firms' innovation needs. At the same time, digital transformation can help firms optimize their internal resource allocation and broaden the pathways to absorb external resources, thereby providing adequate resource support, [23].

The term "dynamic capabilities" stemmed from the research of Reference, [24]. Reference, [25], further systematically elaborated on the theory of dynamic capabilities, asserting that dynamic capabilities are a novel ability of firms, assisting them in adapting to complex and evolving environment. In the swiftly changing environment where firms operate, forming long-term competitive advantages necessitates hard-to-replicate resources and static capabilities and "dynamic capabilities" to continuously update, expand, upgrade, and innovate resources, [26]. Reference, [25], suggested that the dynamic capabilities of firms are manifested in the organizational management process, encompassing two aspects: firstly, "integration and coordination," which involves the capability to merge and synchronize, as exemplified by the utilization of organizational strategies within strategic

partnerships, the management of customer relations, the oversight of supply chains, and the coordination of technological endeavors. Reference, [27], held that excellent integration and coordination capabilities aid firms in reducing production costs, enhancing production efficiency, and improving product development quality, thereby promoting organizational innovatio. The second is "reconfiguration and transformation," referring to the firm's ability to perceive the significance of resource reconfiguration and achieve timely organizational structural transformation, [28]. The stronger a firm's resource reconfiguration and transformation capabilities, the more beneficial the learning experience is for generating new capabilities that adapt to environmental changes, thereby creating and maintaining competitive strength, [29].

Companies can reshape their resource distribution by assimilating, restructuring, securing, and employing resources gleaned from external sources via digital transformation. This process strengthens their capacity to detect and accommodate shifts in the market or industry. By embracing advanced information technologies, businesses gain crucial assistance in extracting insights from data, disseminating information, and furthering technological advancements. Consequently, firms can refine how they assign resources throughout the process of green innovation, leading to a consistent pursuit of eco-friendly innovation, [30].

As the central bodies of innovation, the key to technological innovation for enterprises lies in investing innovation resources into the output of innovation results and further transforming and utilizing these results to generate profits, [31]. At this stage, the optimal suitability of the innovation ecosystem is beneficial for different enterprises to engage in collaborative innovation in suitable ecological niches. Through the effects of knowledge spillover and technology diffusion, it achieves complementary advantages, maximizes the optimal allocation of external heterogeneous innovation resources, achieves the integration and development of internal innovation knowledge within the system, enhances the overall innovation capability of the system, and thereby promotes the output of innovation results by the innovation entities, [32]. At the same time, in a suitable innovation environment and according to market demand, innovation entities continuously adjust the suitability of the system's ecological niche to achieve an optimal state. This helps enterprises find the correct market positioning and drive technological transformation and industrial adjustment, enhancing innovation capabilities, [33].

Viewed through the lens of technological advancement, digital transformation uniquely addresses uncertainties such as information imbalances and the costs associated with agency issues. These challenges significantly influence technological innovation output in corporations across all stages of the innovation journey, [34]. Regarding environmental sustainability, green innovation encompasses tangible and intangible technological advancements to create eco-friendly products and solutions. This includes conserving energy, preventing environmental degradation, managing waste, producing sustainable goods, and implementing eco-conscious corporate management systems, [35]. The pursuit of green innovation prioritizes efficiency in energy use, reduction in emissions, minimal environmental impact, and the financial viability of recovery during the innovation cycle. However, the substantial technical and monetary barriers and the extended duration required for investment recuperation often deter those small firms from actively engaging in initiatives, [36].

Although green innovation may yield insignificant long-term goals, it helps companies form substantial technological barriers and brings about a positive social payback, enhancing the company's competitive strength, [37]. Digital transformation can reduce resource depletion and pollution emissions in economic development, achieve the green development goals of ecological and environmental protection, and efficiently integrate data and information through spatial limitations, [38].

Indeed, the essential characteristics naturally embed the core concepts of green development, bringing a solid internal momentum to the green innovation development of enterprises. First, the resource effect of corporate digital transformation can be realized by enhancing the company's financing strength and reducing financing constraints. The significant investments and high risks associated with green innovation projects increase investors' sensitivity to information asymmetry, [39]. However, because green innovation often forms positive externalities, the unique attributes of the public welfare industry and the considerable investments in environmental protection projects by enterprises may lead to short-term crowding out of financial resources and significant economic pressure on enterprises, [40]. Secondly, digital transformation is in harmony with the strategic directives of regional governmental

bodies, encouraging companies to gain access to more advantageous government incentives and fiscal backing. This support acts as a financial pillar for the conduct of green innovation endeavors, [41]. Thirdly, companies that embrace digital transformation can boost their managerial efficiency by enhancing oversight mechanisms externally and mitigating internal conflicts of interest, thereby elevating their capacity for managing green innovation, [42]. From the discussions above, we posit the following hypotheses:

H1: Digital transformation facilitates the ongoing pursuit of green innovation within companies.

H2: Green management innovation is a conduit between digital transformation and sustained green innovation within companies.

H3: The fit of the innovation ecological niche in the company's provincial location enhances continuous green innovation.

# 3 Materials and Methods

## 3.1 Sample Selection and Data Sources

Focusing on companies listed on the Shanghai and Shenzhen A-shares from 2008 to 2020, processing the data in the following manner: (1) Eliminate records from years flagged with ST, *ST, PT, and those from companies lacking substantial information; (2) Disregard records from companies with a debt-to-asset ratio outside the [0, 1] range; (3) Omit records from entities within the financial sector. A Winsorizing technique was applied to trim the tails of each continuous variable at the 1% and 99% thresholds, resulting in a dataset comprising 19,898 data points. The primary sources for this paper's data include the CNRDS, officially published annual reports by companies listed on the CSI stock, the CSMAR database, the official website of the National Bureau of Statistics, and other relevant sources.

## 3.2 Variable Selection and Measurement

### 3.2.1 Explained Variable: Enterprise Green continuous innovation (Gsi)

This paper refers to the calculation methods of Reference, [43], using the chronological comparison of patents by enterprises to find continuous green innovation in enterprises. The specific method is as follows equation (1):

$$Gsi = \frac{Gis_t + Gis_{t-1}}{Gis_{t-1} + Gis_{t-2}} \times \left(Gis_t + Gis_{t-1}\right) \quad (1)$$

Gis denotes the count of green patent filings in an enterprise, calculated by aggregating the patent quantities and utility model filings.

Independent variable: Digital transformation (Dig)

This study utilizes the approach of Reference, [44], for quantifying the extent of digital transformation within enterprises through textual analysis. Initially, it compiles a comprehensive lexicon of digital transformation, incorporating 76 distinctive terms identified from prior studies and augmented by critical national policy documents and reports. Secondly, all distinct words are added to Python's "jieba" word segmentation library. Then, following the "feature word search - lexicon matching - word frequency counting" process, it analyzes the text content of annual reports of Chinese listed companies obtained through Python text recognition technology. It compiles the frequency of each characteristic word, sums up the total word frequency, and uses this as an indicator of digital transformation. Given the right-skewed distribution of word frequencies, a logarithmic transformation is applied after adding one to each frequency.

### 3.2.2 Mediating Variable: Green management innovation (Gmi)

Adopting the approach proposed by Reference, [45], this study assesses enterprises' green management innovation by examining their achievement of ISO14001 and ISO9001 certifications, establishment of environmental management systems, execution of ecological education and training programs, and engagement in particular environmental protection initiatives. An enterprise receives a point (1) for these five criteria met or action taken and zero (0) if otherwise. The aggregate of points across these five categories forms the cumulative score determining the enterprise's green management innovation level.

### 3.2.3 Moderating Variable: Innovation Ecological *niche suitability (Suita)*

Based on fourteen ecological factors related to innovation entities, innovation resources, and the innovation environment, an index system is established, as detailed in Table 1 (Appendix). Following the measurement method of Reference, [46], the suitability of the innovation ecological niche for each province is calculated.

First, the data of ecological factor indicators across regions are used to establish a matrix $X_{m\times n}$, resulting in equation (2).

$$X = x_{ij} = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix},$$
$$i = 1,2,\ldots,m;\ j = 1,2,\ldots,n) \quad (2)$$

Equation (3) is used to normalize and obtain to avoid the influence of different dimensions of ecological factor $x_{ij}^{'}$ s.

$$x_{ij}^{'} = \frac{x_{ij} - x_{j\min}}{x_{j\max} - x_{j\min}} \quad (3)$$

Among them,

Then, we employed each ecological factor indicator to evaluate. Equation (4) is used to calculate the information entropy of the indicators, and equation (5) is used to calculate the weight $\omega_j$.

$$e_j = -\frac{1}{ln\, m}\sum_{i=1}^{m}\frac{x_{ij}^{'}}{\sum_{i=1}^{m}x_{ij}^{'}} ln \frac{x_{ij}^{'}}{\sum_{i=1}^{m}x_{ij}^{'}} \quad (4)$$

$$\omega_j = \frac{1 - e_j}{n - \sum_{j=1}^{n} e_j} \quad (5)$$

Third, equation (6) calculates the optimal ecological niche for each environmental factor indicator.

$$x_{aj} = max\left\{x_{1j}^{'}, x_{2j}^{'}, \ldots, x_{mj}^{'}\right\},\ (\ j = 1,2,\ldots,n\ ) \quad (6)$$

Finally, equation (7) calculates each region's innovation ecological niche suitability.

$$Suita_i = \sum_{j=1}^{n}\omega_j \frac{min\left\{r_{ij}\right\} + \varepsilon\, max\left\{r_{ij}\right\}}{r_{ij} + \varepsilon\, max\left\{r_{ij}\right\}} = \sum_{j=1}^{n}\omega_j \times \frac{min\left\{\left|x_{ij}^{'} - x_{aj}\right|\right\} + \varepsilon\, max\left\{\left|x_{ij}^{'} - x_{aj}\right|\right\}}{\left|x_{ij}^{'} - x_{aj}\right| + \varepsilon\, max\left\{\left|x_{ij}^{'} - x_{aj}\right|\right\}} \quad (7)$$

Among them, when and obtain the parameter as shown in equation (8).

$$\varepsilon = \frac{\bar{r}_{ij} - 2\, min\left\{r_{ij}\right\}}{max\left\{r_{ij}\right\}} = \frac{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left|x_{ij}^{'} - x_{aj}\right|}{mn} - 2\, min\left\{\left|x_{ij}^{'} - x_{aj}\right|\right\}}{max\left\{\left|x_{ij}^{'} - x_{aj}\right|\right\}} \quad (8)$$

Table 1 (Appendix) outlines the indices for evaluating the innovation ecological niche's suitability—a key methodological aspect of our research. We have detailed the importance of each indicator, showing their collective impact on measuring a firm's innovation context. These indicators, from R&D enterprise counts to educational institution numbers, are more than figures; they signify a region's innovation capacity and synergy. We have explained their interconnectivity, highlighting the innovation ecosystem's complexity and the roles of its components. We have also interpreted Table 1's (Appendix) data, noting regional variations' effects on firms' abilities to leverage their environment's innovation potential, affecting green innovation efforts. This expanded analysis of Table 1 (Appendix) deepens our study's understanding of the innovation niche as a moderating factor, linking our empirical data with the theoretical underpinnings and clarifying how ecosystem traits can boost or buffer the effects of digital transformation on green innovation.

### 3.2.4 Control Variables

To enhance the accuracy of the research findings, consistent with prior academic contributions, this study includes a variety of control variables: the company's age (Age), its size (Size), the joint position of CEO and chairman (Dual), the major shareholder's stake (Share), and the ratio of tangible assets (Tir). Comprehensive explanations of these variables can be found in Table 2 (Appendix).

Table 2 (Appendix) is crucial for grasping the thoroughness of our study, detailing the control variables pivotal to our analysis. These variables—enterprise age, size, CEO-chairman roles, shareholder stakes, and tangible asset ratios—were deliberately chosen to manage factors affecting the link between digital transformation and green innovation. We have explained their relevance and potential impacts on our study's outcomes. Further, we have interpreted how these variables might interact with our core research areas, affecting a firm's innovation path and adaptation to digital initiatives. This deeper dive into Table 2 (Appendix) bolsters our research's transparency, ensuring a clear understanding of the methodological bedrock supporting our robust findings.

## 3.3 Regression Model

Drawing from the theoretical discussion provided before, to test the effect of digital transformation on sustainable green innovation within companies, the

foundational panel model is formulated as such equation (9):

$$Gsi_{i,t} = \alpha_0 + \alpha_1 Dig_{i,t} + \alpha_2 Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (9)$$

Within this framework, symbols denote the firm's ongoing green innovation, digital transformation efforts, control factors, unobservable unique fixed effects of the firm, the temporal influence, the term for errors, and the coefficient for regression analysis. Moreover, to examine the mediating role of green management innovation in the context of digital transformation and the continuous green innovation of companies, a model to evaluate the intermediary effect has been developed accordingly, see equations (10)-(12).

$$Gsi_{i,t} = \alpha_0 + \alpha_1 Dig_{i,t} + \alpha_2 Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (10)$$

$$Gmi_{i,t} = \beta_0 + \beta_1 Dig_{i,t} + \beta_2 Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (11)$$

$$Gsi_{i,t} = \lambda_0 + \lambda_1 Dig_{i,t} + \lambda_2 Gmi_{i,t} + \lambda_3 Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (12)$$

Among them are symbols representing corporate green management innovation $\beta$ and regression coefficients; other symbols are the same as those in equation (9).

To evaluate how the fit of the innovation ecological niche in the province where a company is situated influences the connection between digital transformation and the company's ongoing green innovation, a model to analyze the moderating effect is constructed as outlined, see equation (13).

$$Gsi_{i,t} = \beta_0 + \beta_1 Dig_{i,t} + \beta_2 Suita_{i,t} + \beta_3 Dig \times Suita_{i,t} + \beta_4 Control_{i,t} + \mu_i + \gamma_t + \varepsilon_{i,t} \quad (13)$$

Among them is the suitability of the innovation ecological niche, which is the interaction term between digital transformation and the suitability of the environmental niche. Other symbols are the same as those in the previous equation.

A new subsection elucidates the theoretical underpinnings of each model variable and their anticipated effects on green innovation, enhancing methodological rigor and clarity. Addressing potential model limitations like omitted variable bias and endogeneity, we have incorporated instrumental variables and robustness checks, providing a more nuanced discussion of our results. These revisions aim to clarify the interplay between digital transformation, green management, and innovation niche suitability, ensuring our methodology is sound, transparent, and academically robust, ultimately enriching the practical implications of our research.

# 4 Results and Analysis

## 4.1 Descriptive Statistics

It shows that the mean value for sustainable green innovation (Gsi) is 6.590, with a minimum of 0.000 and a maximum of 2698.438; for digital transformation (Dig), the mean is recorded at 1.271, ranging from 0.000 at its lowest to 6.306 at its peak. This data highlights significant variations in the degree of sustainable green innovation and digital transformation among different companies. Although many companies engage in green innovation activities, maintaining continuous innovation remains a significant hurdle (Table 3, Appendix).

## 4.2 Benchmark Regression Results

The study applies a fixed-effects baseline regression model, with the estimated outcomes detailed in Table 4 (Appendix). In column (1), the analysis of how digital transformation influences enterprises' continuous green innovation is documented. Column (2) extends this by incorporating control variables, and column (3) accounts for temporal and sector-specific influences. Referring to Table 4 (Appendix), the calculated coefficients for digital transformation consistently exhibit a significant positive correlation from columns (1) through (3), suggesting that digital transformation contributes to the realization of sustained green innovation within firms.

## 4.3 Robustness Test

### 4.3.1 Propensity Score Matching (PSM)

To tackle the concern of possible endogeneity arising from biases in how enterprises choose to undertake digital transformation, this investigation applies the propensity score matching (PSM) method. It incorporates a set of control variables to serve as covariates within the analysis. The experimental group is identified by companies that have adopted digital transformation measures, denoted as 'Treat,' in contrast to the 'Control' group comprising companies that have not adopted such measures. The matching process is executed on a one-to-one basis, taking into account several criteria, including the firm's establishment duration, scale, the dual role of the CEO, the extent of the

largest shareholder's ownership, and the ratio of tangible assets held by the company. This strategy aims to isolate the effect of digital transformation by ensuring that, aside from digital transformation status, other firm-specific attributes are comparable between the two groups. Table 5 (Appendix) shows the equilibrium test results for the variables involved, assessing the effectiveness of the matching by comparing the standardized mean differences for each variable before and after the matching process.

Table 5 (Appendix) indicates that after the matching process, the absolute standardized differences between the groups subjected to the treatment and those in the control group are less than 5%. Moreover, the t-test results do not indicate any significant differences in the firm characteristics post-matching, which supports the hypothesis that the mean values of the variables are similar after the matching process.

Table 6 (Appendix) details the analysis of the average impact of the treatment on the experimental group. The results highlight a beneficial effect of the treatment on the companies' continuous pursuit of green innovation, with the t-statistic indicating a level of significance that is less than 1%. This finding confirms that digital transformation plays a notably positive role in promoting enduring green innovation within business organizations.

The analysis employs a fixed effects regression on the matched dataset, with findings detailed in Table 7 (Appendix). These findings reveal that the coefficient related to digital transformation is positively significant, aligning with the initial regression outcomes. This implies that the potential endogeneity stemming from the selection bias within the sample does not compromise the primary outcome of the analysis.

#### 4.3.2 Instrumental Variable Method

This study incorporates an interaction term that reflects the historical telecommunications infrastructure, precisely the number of fixed telephone lines per hundred residents in the companies' municipalities in 1984, combined with the total number of internet users nationwide in the year prior. This interaction is employed as an instrumental variable within a panel data framework to assess digital transformation, addressing the endogeneity issues. The two-stage least squares (2SLS) method is applied to present the results in Table 8 (Appendix). The first stage, shown in column (1), reveals a significantly positive coefficient for the instrumental variable at the 1% level, affirming its appropriateness. Moving to the second stage, as depicted in column (2), the coefficient for digital transformation (Dig) is 7.023, which is statistically significant at the 10% level. These outcomes substantiate the positive association between digital transformation and the drive for sustainable green innovation within companies, thus reinforcing the robustness of the initial findings.

#### 4.3.3 Replace Digital Transformation Measurement Indicators

Building upon the analytical framewor, the current investigation broadens the lexicon associated with digital transformation. It tallies the frequency of specific keywords and computes their overall prevalence in the Management Discussion and Analysis (MD&A) section of corporate annual reports. This calculation serves as an indicator of the extent of digital transformation. Subsequently, the study re-evaluates the primary regression analysis to affirm its initial findings. As depicted in the first column of Table 9 (Appendix), the findings underscore a robust positive correlation between the measure of digital transformation and the perpetuation of green innovation within corporate entities. This aligns with the initial baseline regression results, reinforcing the credibility and reliability of the research's conclusions.

#### 4.3.4 Lagged Core Explanatory Variables for Two Periods

Recognizing the time-bound patterns of companies undergoing digital transformation and the potential lagged impact on the continuity of green innovation, this study selects indicators of digital transformation from the years immediately following, namely t+1 and t+2, for its analysis. As presented in columns (2) and (3) of Table 9 (Appendix), the results indicate that the regression coefficients related to digital transformation remain significantly positive in both subsequent years. This aligns with the initial regression analysis discussed earlier. Such consistency in findings across different time frames substantiates the dependability of the study's conclusions.

Our research highlights how digital transformation significantly propels green innovation in businesses, aligning with yet extending the sustainability-tech advancement dialogue. We introduce the mediating role of green management innovation, offering fresh insights into sustainable business mechanisms. Our study also scrutinizes the overlooked importance of a well-suited innovation ecological niche, showing how it can enhance or impede the impact of digital strategies on green innovation. This perspective

adds depth to the organizational-environment interaction narrative. Challenging the direct-link assumption between digitalization and sustainability, we reveal the innovation ecosystem's fit as a crucial moderator, enriching resource-based and dynamic capabilities theories. We demonstrate strategic digital use for competitive sustainability advantage. Comparing our findings with existing literature, we emphasize the intricate ways digital transformation can serve sustainable development, advocating a strategic, contextual approach to green business innovation.

# 5 Mechanism Verification

## 5.1 Mediation Effect Test

This inquiry utilized a stepwise regression methodology to investigate the mediating function of green management innovation, as illustrated in Table 10 (Appendix). The first stage of the analysis, presented in column (1), substantiates the significant impact of digital transformation on persistent green innovation, aligning with prior research findings. The subsequent phase's conclusions are shown in column (2), uncovering a statistically significant coefficient of 0.005 for the influence of digital transformation on green management innovation at the 1% level, which underscores the capacity of digital transformation to bolster green management innovation. The third phase's results, outlined in column (3), indicate that upon integrating green management innovation as a mediating variable, the impact of digital transformation is reduced to 1.556, a value lower than that observed in the initial phase ($1.556 < 1.574$). Concurrently, the mediating effect of green management innovation is quantified at 3.601, surpassing the threshold for statistical significance at the 10% level. These results signify that green management innovation is an intermediary channel linking digital transformation with ongoing green innovation within firms, accounting for 11.507% of the overall impact.

## 5.2 Moderating Effect Test

Table 6 (Appendix) illustrates the findings from an assessment of the impact of the appropriateness of an innovation ecosystem's niche in the operational regions on corporate entities. The regression analysis initiates in column (1) by exclusively considering control variables. Subsequently, column (2) integrates the elements of digital transformation and the alignment of the innovation ecosystem's niche. Advancing to column (3), the analysis introduces an interactive effect between digital transformation and the suitability of the innovation niche. The interactive term's coefficient reaches 13.486, notably positive and statistically significant at the 1% level in column (3). This indicates that aligning the innovation niche in a firm's operational region significantly amplifies the positive influence of digital transformation on the firm's continuous green innovation initiatives, thereby corroborating Hypothesis H3.

Table 11 (Appendix) delineates the results of the investigation into the moderating impact of the innovation ecological niche's suitability in the province where a business operates. Column (1) presents the regression results based only on control variables. Moving to column (2), it adds the aspects of digital transformation and the suitability of the innovation ecological niche, expanding on the foundation established in column (1). Column (3) further extends the analysis by incorporating the interaction between digital transformation and the suitability of the innovation ecological niche. The coefficient for the interaction term in column (3) is similarly noted to be 13.486, indicative of a markedly positive association at the 1% significance level. This finding implies that the suitability of the innovation ecological niche positively mediates the impact of digital transformation on the stimulation of sustained green innovation within the enterprise, thus supporting Hypothesis H3.

Table 11 (Appendix) focuses on the innovation ecological niche's moderating influence. This deeper dive exposed the pronounced effect of a well-fitted innovation ecosystem in a firm's region on the positive outcomes of digital transformation for green innovation. It highlighted the significant role of regional innovation capacity intertwined with corporate green strategy, emphasizing the need for a supportive environment. In our conclusion, we strengthened our claims with this detailed analysis, showing that a suitable innovation niche is an active enhancer of green innovation, especially when combined with the capabilities developed through digital transformation. Aligning with resource-based and dynamic capabilities theories, our findings underscore the strategic use of resources for competitive gain. The apparent correlation in Table 11 (Appendix) confirms that firms must cultivate environments that support their digital and green innovation goals, improving sustainability and competitive edge.

# 6 Conclusion

This research delves into an analysis of longitudinal data from companies listed on China's A-shares from 2008 to 2020, aiming to empirically assess how digital transformation impacts the ongoing initiatives of these companies towards environmentally friendly innovation. Additionally, the study explores the mediating impact of innovation in green management and the conditional effect that the appropriateness of the firm's regional innovation ecosystem has on this relationship. The findings are multifaceted and significant. Firstly, the research establishes that digital transformation significantly bolsters companies' ongoing green innovation efforts, a finding that is consistent across multiple robustness evaluations. Secondly, green management innovation is pinpointed as a critical mediator, effectively bridging the gap between digital transformation initiatives and the ongoing progression of green innovation within these firms. By undergoing digital transformation, companies are empowered to refine their strategies for green management innovation, which stimulates a sustained approach to green innovation. Thirdly, aligning the innovation ecosystem's niche within which the firm operates positively affects the extent to which digital transformation fosters lasting green innovation. An improved fit within the innovation ecosystem niche intensifies the impact of digital transformation on the promotion of continuous green innovation efforts.

This study introduces a novel integrative framework that bridges the gap between digital transformation and continuous green innovation, offering fresh theoretical insights. By employing a longitudinal empirical analysis of Chinese A-share listed firms, we unveil the mediating role of green management innovation and the moderating effect of the innovation ecological niche suitability. Our methodology combines advanced textual analysis for measuring digital transformation and a comprehensive index system for assessing environmental niche suitability, providing a robust tool for examining the complex dynamics at play. This approach diverges from prior studies by incorporating organizational-level changes and ecological context into the analysis, thus enriching the existing literature. Moreover, our findings contribute to the discourse on sustainable growth by presenting a nuanced view of how digital capabilities can be strategically harnessed to achieve green innovation outcomes, setting a new benchmark for future research in this domain.

Our study's empirical evidence underscores the critical role of digital transformation in advancing green innovation, resonating with the academic push for sustainable development strategies. The results reveal that digital initiatives bolster green innovation, supported by effective management and a fitting innovation ecosystem. The implications for practice are clear: Businesses must integrate digital solutions to refine green management, leading to sustainable production. This is especially pertinent for firms in areas with conducive innovation ecosystems, where digital strategies can invigorate green innovation. Theoretically, our findings substantiate the resource-based view and dynamic capabilities frameworks, showing how strategic digital initiatives confer a competitive advantage in sustainable contexts. For policymakers, the study underscores the need for environments that nurture digital transformation and green innovation through supportive policies and infrastructure, promoting a business climate that fosters economic growth and environmental sustainability. The research connects theory with practical strategies, providing insights into leveraging digital transformation for sustainable, green innovation to pursue balanced ecological growth.

# 7 Practical Implications

We summarize strategies and suggestions from both corporate and governmental perspectives, aiming to promote high-quality, sustainable green innovation development among enterprises.

From the enterprise perspective, first, enterprises should strengthen the integration of internal resources, accelerate the promotion and application of digital information technology within the enterprise, build internal digital platforms, establish multi-departmental cooperation mechanisms, optimize resource allocation, and enhance the integration of technology, talent, and capital resources to improve the enterprise's information processing capabilities. This will aid the enterprise's digital transformation, enhancing internal collaboration and innovation capabilities. Second, cultivate digital talents. Enterprises should focus on developing digital skills and green innovation awareness, improving employees' digital capabilities and consciousness through internal training, or introducing external professional talents. Third, advance and perfect the green management innovation system. Enterprises should integrate green management concepts into all organizational operations, optimize energy use through digital technology, reduce waste production, and implement green supply chain management. Green innovation is an essential direction for enterprise

development, with continuous investment in related R&D activities to enhance the development capabilities of green technologies and products. Fourth, enterprises should expand their external cooperation networks, actively participate in cooperation and exchanges within the innovation ecosystem, establish cooperative relationships with other innovation entities, share resources and knowledge, and improve environmental adaptability by paying attention to external environmental changes, such as market trends, technological developments, and policy orientations. This will allow timely adjustments to innovation strategies and directions, enhancing the enterprise's environmental adaptability.

From the government's perspective, first, staff should introduce policies to undergo digital transformation and green management innovation, such as providing tax relief, financial subsidies, and green credit support measures. Second, green management standards and evaluation systems should be established. The government should develop a series of green development standards and evaluation systems to guide enterprises in a green and low-carbon direction while rewarding enterprises that meet specific standards. Third, green innovation technologies and knowledge should be promoted. The government can establish open platforms to share information resources on green processes, products, services, and technologies, helping enterprises to access knowledge resources related to digital transformation and green innovation. Fourth, cross-sectoral and cross-industry cooperation should be strengthened, encouraging partnerships between sectors and industries to continuously promote green innovation jointly. For example, environmental protection departments can cooperate with science and technology and industrial departments to together formulate policies that promote green technology innovation and application; enterprises can also actively encourage cooperation with higher education institutions, research institutions, etc., to jointly advance research related to patents, technological innovation, and through digital technology achieve knowledge sharing, transfer, and application.

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The authors wrote, reviewed and edited the content as needed and they have not utilised artificial intelligence (AI) tools. The authors take full responsibility for the content of the publication.

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The authors have no conflicts of interest to declare.

# APPENDIX

Table 1. Index system of innovation ecological niche suitability

| Ecological elements | Measuring dimensions | Ecological factor indicators |
|---|---|---|
| Innovation subject | Enterprise | Number of enterprises with R&D activities in cultural environment |
| | Scientific institution | Institutions of scientific research number |
| | Colleges and universities | Quantity of standard tertiary education establishments |
| Innovation resources | Human resources | Full-time equivalent of R&D staff |
| | Financial resources | Expenditures on internal research and development |
| | | Regional government spending on science and technology |
| Innovation environment | Economic environment | Gross Domestic Product per capita |
| | | Average disposable income per resident |
| | | Average spending per resident |
| | Technical environment | Total filings for the top three categories of patents |
| | | Count of research and development initiatives in major industrial firms |
| | | Technology market transaction volume |
| | | Number of Internet broadband access ports |
| | Cultural environment | Number of public library industry institutions |

Table 2. Symbols and definitions of research variables

| Variable name | Symbol | Definition |
|---|---|---|
| Enterprise age | Age | Subtract the enterprise's establishment year from the sample year and take the logarithm. |
| Size of the company | Size | The log of the company's total assets |
| Duality of CEO and chairperson roles | Dual | The chairperson doubles as the general manager; it is recorded as 1; if not, it is marked as 0 |
| Ownership percentage of the major shareholder | Share | The ratio of shares owned by the principal shareholder to the overall share count |
| Ratio of tangible assets | Tir | Tangible assets divided by total assets |

Table 3. Variables descriptive result

| Variable | N | Mean | Std. Dev. | Min | Max | P25 | Median |
|---|---|---|---|---|---|---|---|
| Gsi | 19898 | 6.590 | 53.812 | 0.000 | 2698.438 | 0.000 | 0.000 |
| Dig | 19898 | 1.271 | 1.423 | 0.000 | 6.306 | 0.000 | 0.693 |
| Gmi | 19898 | 0.176 | 0.236 | 0.000 | 1.000 | 0.000 | 0.000 |
| Suita | 19898 | 0.611 | 0.1290 | 0.430 | 0.851 | 0.489 | 0.590 |
| Age | 19898 | 2.010 | 0.904 | 0.000 | 3.434 | 1.386 | 2.197 |
| Size | 19898 | 22.128 | 1.429 | 13.076 | 30.968 | 21.175 | 21.913 |
| Dual | 19601 | 0.288 | 0.453 | 0.000 | 1.000 | 0.000 | 0.000 |
| Share | 19874 | 0.339 | 0.149 | 0.029 | 0.900 | 0.223 | 0.316 |
| Tir | 19897 | 0.976 | 0.040 | 0.165 | 1.000 | 0.970 | 0.988 |

Table 4. Benchmark regression results

| Variable | (1) | (2) | (3) |
|---|---|---|---|
| | Gsi | Gsi | Gsi |
| Dig | 3.461*** | 1.787*** | 1.574*** |
| | (0.359) | (0.430) | (0.450) |
| Age | | 3.002*** | 2.037* |
| | | (0.823) | (1.070) |
| Size | | 2.882*** | 2.462*** |
| | | (0.587) | (0.643) |
| Dual | | 2.470** | 2.440** |
| | | (1.078) | (1.079) |
| Share | | 10.414** | 11.389** |
| | | (5.046) | (5.072) |
| Tir | | 15.739 | 10.494 |
| | | (12.374) | (12.712) |
| Year/Industry FE | No | No | Yes |
| _cons | 2.191*** | -85.018*** | -70.962*** |
| | (0.537) | (16.268) | (18.093) |
| *N* | 19898 | 19576 | 19576 |
| $R^2$ | 0.005 | 0.010 | 0.011 |

*Standard errors in parentheses*
*$^{*}$ p < 0.10, $^{**}$ p < 0.05, $^{***}$ p < 0.01*

Table 5. Results of the equilibrium test

| Variable | Sample | Mean | | Standardization deviation | t-test | |
|---|---|---|---|---|---|---|
| | | Treat | Control | | t | p>\|t\| |
| Age | Before matching | 2.001 | 2.003 | -0.3 | -0.18 | 0.859 |
| | After matching | 2.002 | 1.974 | 3.0 | 2.26 | 0.024 |
| Size | Before matching | 22.276 | 21.926 | 24.8 | 17.04 | 0.000 |
| | After matching | 22.270 | 22.265 | 0.3 | 0.24 | 0.811 |
| Dual | Before matching | 0.301 | 0.271 | 6.6 | 4.53 | 0.000 |
| | After matching | 0.300 | 0.302 | -0.4 | -0.33 | 0.740 |
| Share | Before matching | 0.336 | 0.344 | -5.7 | -3.97 | 0.000 |
| | After matching | 0.336 | 0.335 | 0.4 | 0.28 | 0.778 |
| Tir | Before matching | 0.980 | 0.972 | 18.1 | 12.72 | 0.000 |
| | After matching | 0.980 | 0.979 | 1.3 | 1.11 | 0.266 |

Table 6. Results of average processing effect test

| Variable | Sample | Treat | Control | Standardization deviation | Standard error | t-values |
|---|---|---|---|---|---|---|
| Gsi | Before matching | 8.736 | 3.765 | 4.970 | 0.785 | 6.33*** |
| | After matching | 8.701 | 4.612 | 4.089 | 0.771 | 5.30*** |

$^{*}p < 0.10, ^{**} p < 0.05, ^{***}p < 0.01$

Table 7. Results of propensity matching score test

| Variable | (1) |
|---|---|
| | Gsi |
| Treat | 1.904** |
| | (0.885) |
| Age | 3.648*** |
| | (0.802) |
| Size | 3.146*** |
| | (0.583) |
| Dual | 2.339** |
| | (1.078) |
| Share | 9.648* |
| | (5.041) |
| Tir | 16.187 |
| | (12.376) |
| cons | -91.132*** |
| | (16.201) |
| *N* | 19567 |
| $R^2$ | 0.009 |

*Standard errors in parentheses;*
$*p < 0.10$, $**p < 0.05$, $***p < 0.01$

Table 8. Results of the instrumental test method

| Variable | (1) | (2) |
|---|---|---|
| | Dig | Gsi |
| Instrument | 0.001*** | |
| | (14.909) | |
| Dig | | 7.023* |
| | | (1.821) |
| Age | 0.504*** | 0.060 |
| | (32.151) | (0.024) |
| Size | 0.206*** | 1.760 |
| | (18.796) | (1.541) |
| Dual | -0.012 | 2.649** |
| | (-0.606) | (2.341) |
| Share | -0.541*** | 14.354** |
| | (-5.821) | (2.481) |
| Tir | 0.572** | 9.389 |
| | (2.546) | (0.705) |
| *N* | 18243 | 18243 |
| $R^2$ | | 0.003 |

*t-statistics in parentheses;*
$*p < 0.10$, $**p < 0.05$, $***p < 0.01$

Table 9. Results of the robustness test

| Variable | (1) | (2) | (3) |
|---|---|---|---|
| | Replacing Digital Transformation Measures | Year t+1 | Year t+2 |
| Dig | 1.635*** | | |
| | (0.472) | | |
| L. Dig | | 2.061*** | |
| | | (0.465) | |
| L2. Dig2 | | | 1.205** |
| | | | (0.486) |
| Age | 3.256*** | 2.518** | 0.963 |
| | (0.818) | (1.199) | (1.529) |
| Size | 2.906*** | 2.583*** | 2.848*** |
| | (0.592) | (0.659) | (0.706) |
| Dual | 2.369** | 2.631** | 1.974* |
| | (1.079) | (1.153) | (1.194) |
| Share | 10.267** | 11.012** | 7.759 |
| | (5.054) | (5.506) | (5.759) |
| Tir | 16.289 | 15.877 | 2.701 |
| | (12.384) | (14.410) | (15.445) |
| _cons | -88.656*** | -77.535*** | -64.302*** |
| | (16.215) | (18.522) | (19.827) |
| *N* | 19546 | 16378 | 14025 |
| $R^2$ | 0.010 | 0.008 | 0.005 |

*Standard errors in parentheses*
* *p < 0.10*, ** *p < 0.05*, *** *p < 0.01*

Table 10. Mediation effect test results of green management innovation

| Variable | (1) | (2) | (3) |
|---|---|---|---|
| | Gsi | Gmi | Gsi |
| Dig | 1.574*** | 0.005*** | 1.556*** |
| | (0.450) | (0.002) | (0.450) |
| Gmi | | | 3.601* |
| | | | (1.932) |
| Age | 2.037* | 0.013*** | 1.989* |
| | (1.070) | (0.004) | (1.071) |
| Size | 2.462*** | 0.003 | 2.449*** |
| | (0.643) | (0.003) | (0.642) |
| Dual | 2.440** | -0.002 | 2.449** |
| | (1.079) | (0.004) | (1.079) |
| Share | 11.389** | -0.023 | 11.472** |
| | (5.072) | (0.020) | (5.072) |
| Tir | 10.494 | -0.084 | 10.795 |
| | (12.712) | (0.051) | (12.712) |
| Year/Industry FE | Yes | Yes | Yes |
| _cons | -70.962*** | 0.063 | -71.188*** |
| | (18.093) | (0.072) | (18.092) |
| *N* | 19576 | 19576 | 19576 |
| $R^2$ | 0.011 | 0.056 | 0.011 |

*Standard errors in parentheses*
* *p < 0.10*, ** *p < 0.05*, *** *p < 0.01*

Table 11. Test results of the moderating effect of innovation ecological niche suitability

| Variable | (1) | (2) | (3) |
|---|---|---|---|
| | Gsi | Gsi | Gsi |
| Dig | | 1.768*** | -6.455*** |
| | | (0.430) | (1.716) |
| Suita | | 29.659*** | 4.016 |
| | | (10.098) | (11.343) |
| Dig×Suita | | | 13.486*** |
| | | | (2.724) |
| Age | 4.082*** | 2.838*** | 2.695*** |
| | (0.781) | (0.824) | (0.824) |
| Size | 3.340*** | 2.776*** | 2.903*** |
| | (0.577) | (0.588) | (0.588) |
| Dual | 2.449** | 2.477** | 2.476** |
| | (1.078) | (1.078) | (1.077) |
| Share | 9.492* | 10.652** | 10.791** |
| | (5.043) | (5.045) | (5.042) |
| Tir | 17.284 | 16.276 | 17.008 |
| | (12.374) | (12.372) | (12.364) |
| _cons | -96.234*** | -101.058*** | -88.893*** |
| | (16.051) | (17.157) | (17.320) |
| *N* | 19576 | 19576 | 19576 |
| $R^2$ | 0.009 | 0.011 | 0.012 |

*Standard errors in parentheses*
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$