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*Research article*

# The impact of digital technology on enterprise green innovation: quality or quantity?

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**Abstract:** Digital technology promotes the dual transformation of enterprise digitization and greenization, thereby promoting the synergistic efficiency between the digital economy and the green economy. This paper collected financial data from 2010 to 2021 from Chinese listed companies on the Shanghai and Shenzhen stock exchanges. Through an in-depth semantic analysis of textual data, the study constructed an index to measure the level of enterprise digitization. Utilizing panel data models, the paper explored the impact of digital technology on enterprise green innovation and its mechanisms from the perspectives of quality and quantity. The research findings are as follows: (1) Digital technology significantly enhances the capability of enterprises for green innovation, with an emphasis on quality rather than quantity; (2) digital technology effectively alleviates financing constraints and information constraints, thereby enhancing the level of enterprise green innovation, but the former's effect is limited to small and medium-sized enterprises; (3) the "quality over quantity" effect of digital technology on enterprise green innovation is more pronounced in state-owned enterprises, non-heavy polluting industries, and enterprises located in regions with moderate to low levels of economic development.

**Keywords:** digital technology; green innovation; text mining; financing constraints; information constraints

**JEL Codes:** C1, C33, Q56

## 1. Introduction

Digitalization has become the main driving force for the green transformation and high-quality development of enterprises. Currently, China's economic development is shifting from "high-carbon growth" to "green development" and from "quantity catch-up" to "quality catch-up". A series of emerging information technologies such as cloud computing and artificial intelligence, which are based on the Internet, play an important role in achieving economic growth, industrial transformation and upgrading, and reducing environmental pollution (Bhattacharya, 2023). Digitalization has become the core force driving high-quality economic development in various countries (Ma & Li, 2022). On the one hand, it can help companies achieve green production (Li et al., 2018), promote green transformation and upgrading of enterprises, and improve ecological efficiency (Han et al., 2021). For example, Amazon AWS, Microsoft Azure, and Google Cloud Platform improve supply chain efficiency and transparency by providing cloud infrastructure and services; green supply chain management achieves digitalization and automation through deep learning algorithms (Wang & Ge, 2022). Digitalization has become an important dynamic force and new engine for enterprises to transform and upgrade from traditional industries to modern service industries and achieve long-term stable development (Sestino et al., 2023). On the other hand, digitalization can help optimize and automate production, marketing, and services, enhance enterprise competitiveness, expand market share, and promote high-quality development of enterprises. For example, by optimizing energy systems through machine learning or improving production process efficiency through intelligent monitoring (Zhang et al., 2020). Also, cloud computing has played an important role in epidemic monitoring, drug research and development, and information dissemination during the fight against the epidemic (Li et al., 2023). Digitalization profoundly affects various activities of enterprises, narrowing the value gap between manufacturing and research and development, as well as marketing and service (Liu et al., 2023), significantly improving enterprise efficiency and green innovation capabilities and promoting high-quality development of enterprises. However, while affirming the positive role of digitalization, we must also recognize the challenges and negative effects it may bring in practice. For example, the increase in the use of resources and energy, as well as waste and emissions from hardware manufacturing, use, and disposal, may cause a negative environmental burden (Chen et al., 2020). Digitalization has also intensified electricity consumption, and a non-clean-dominated energy structure will generate additional carbon emissions, which is unfavorable for sustainable enterprise development (Wu et al., 2023). It can be seen that further research is required for understanding how digital technology affects enterprise green innovation. Therefore, our research focuses on digital technology and enterprise green innovation and aims to answer the following three questions. (1) Can digital technology effectively promote enterprise green innovation, including the impact on the quality and quantity of green innovation? (2) If there is a promoting role, how does digital technology affect enterprise green innovation? (3) Is the impact of digital technology similar under different external environments and enterprise attributes?

Different from traditional measures of digital technology, digital technology measures constructed using text mining techniques have significant advantages. Currently, the definition of digital technology lacks clear and unified definitions. Most scholars use theoretical qualitative digital technology (Xu et al., 2024) or use IPC classification codes (Li et al., 2021) and digital patent vocabularies (Lee et al., 2009) to identify digital patents to reflect digital technology. There are also a few quantitative studies based on the frequency of keywords related to annual reports of listed companies to characterize digital transformation (Feng et al., 2022). Among them, theoretical research is often based on some simplified or idealized assumptions, which may differ from the actual situation and are susceptible to subjective factors; digital patent identification methods may have shortcomings in identification or incorrect identification, and the degree of digital transformation measured by annual report keywords is fundamentally different from the digital technology in concept (Gao et al., 2023). With the development of interdisciplinary integration, many studies in the fields of economics and management have begun to use computer programming techniques, such as data mining and text mining, to extract data information embedded in text and measure the importance of specific keywords to enterprises. In contrast, constructing digital technology indicators through text mining techniques from publicly disclosed corporate information texts will be more rapid, accurate, objective, and cost-effective. On the one hand, it can efficiently process a large amount of text data in batches, discover potential patterns, trends, and rules, and improve the efficiency and accuracy of information retrieval. On the other hand, the Company Law of the People's Republic of China clearly stipulates that the information disclosed by listed companies should be true, accurate, and complete, ensuring that the data source of text mining is publicly available, standardized, transparent, and reliable textual information, effectively meeting the requirements of constructing digital technology indicators.

## 2. Literature review and research framework

### *2.1. Literature review*

The literature closely related to this study can be divided into three categories. The first discusses the factors that affect the green innovation of enterprises, including external and internal environmental factors. The former mainly includes policy promotion (Chen et al., 2022; Fu et al., 2023; Han et al., 2024; Wu et al., 2023), market demand (Kumar et al., 2021; Rizzo et al., 2023), and social pressure (Li et al., 2017; Zhang & Zhu, 2019). Internal environment factors include the enterprise strategy (Broccardo et al., 2023; Lian et al., 2022; Zhang et al., 2022), R&D investment (Li et al., 2023; Liu et al., 2022), and digitalization (Broccardo et al., 2023; Karlilar et al., 2023; Kurniawan et al., 2022; Ning et al., 2023).

The second category explores the relationship between digitalization and innovation capability, which can be divided into macro and micro levels. At the macro level, Wu and Gong (2019) suggested varying impacts of open innovation networks on enterprise innovation capability. Wang and Cen (2022) by constructing endogenous growth models, revealed that overall development of the digital economy promotes the enhancement of innovation levels, albeit with nonlinear effects on innovation performance. Tang et al. (2021) found that the construction of network infrastructure can enhance the quality and efficiency of enterprise innovation by reducing information asymmetry and promoting technology spillovers. At the micro level, studies have explored the promotion of enterprise innovation by digitization from external perspectives such as digital product imports (Chen et al., 2024), digital service trade liberalization (Fang et al., 2023), and global innovation networks (Li et al., 2023). On the other hand, internal perspectives such as digital transformation approaches (Feng et al., 2022; Xue et al., 2022) and enterprise total factor productivity (Wu et al.,

2022) have also been explored to uncover the stage characteristics and intrinsic mechanisms of enterprise innovation capability enhancement.

The third category explores the relationship between digitalization and business innovation, which can be divided into theoretical and quantitative aspects. In terms of theoretical analysis, studies suggest that fundamental changes in product forms (Zhou et al., 2018) and the transformation of traditional business enterprises (Huang et al., 2017) can be facilitated through the integration of digital technology. Positive effects of new generation information technologies such as blockchain on digital supply chain finance innovation (Pal, 2022) and innovative operations of platform-based supply chains (Liu & Peng, 2022) have also been explored. In terms of quantitative analysis, Huang et al. (2023) used data on digital invention patents of Chinese listed companies to indicate that digital technology innovation focusing on new product development, production process improvement, and business model innovation is conducive to enhancing enterprise market value. Yu et al. (2022) used city-level indices and data from the China Household Finance Survey (CHFS) to verify that significant improvements in digital inclusive finance significantly increase the innovation activities and R&D investment of small and microenterprises, stimulating their innovation vitality. Other works have evaluated the perspectives of customer digital transformation and enterprise R&D innovation modes, such as Lai et al. (2023), who found that supplier enterprises drive their own process optimization and product innovation level by imitating the efficient digital production methods and innovation models of their customers, thereby meeting the efficiency and innovation needs of customers' digital transformation. Martínez-Ros and Kunapatarawong (2019) found that, in the digital economic environment, large enterprises are more inclined than small enterprises to engage in iterative innovation, such as improving their products and production processes.

### *2.2. Research gaps and contributions*

Comprehensive analysis of the existing literature indicates that enterprise green innovation is influenced by many factors, with digitalization playing a unique role. The literature reveals the promotion effects and internal mechanism that enhance innovation capability from both macro and micro aspects, encompassing both theoretical and quantitative analysis. It focuses the positive impact of digitalization on business innovation, such as the development of innovative products and the optimization of production processes. However, some research gaps remain: (1) The impact of digital technology on enterprise green innovation has not been fully explored; (2) there is a gap in understanding the potential mechanism of digital technology affecting enterprise green innovation; (3) the combination of heterogeneous discussion and digital background is not close enough. Therefore, the possible innovations of this paper are mainly reflected in the following three aspects:

(1) It enriches the relevant research on the impact of digital technology on enterprise green innovation. Most previous studies have focused on the relationship between digitalization and traditional innovation and discussed the innovation-driving effect of digitalization from the national (Yang et al., 2020), regional (Han et al., 2021; Kohli & Melville, 2019) and enterprise levels (Fang & Liu, 2024; Khin & Ho, 2020). Only a few scholars have focused on how digitalization affected the innovation practice of enterprises in emerging fields such as sustainable development. In addition, some studies have studied the transformation of digital and green from a dual perspective (Ortega-Gras et al., 2021; Sestino et al., 2024). However, few scholars have addressed the subdivision of green innovation of enterprises, and there are still limitations in the measurement of

green innovation ability. This paper divides enterprise green innovation into two dimensions—the quantity of green innovation and the quality of green innovation. From the perspective of digital technology, it tests whether digitalization has a positive impact on enterprise green innovation. This study not only provides a new theoretical perspective and methodology for literature related to dual transformation but also provides an important reference for enterprises in promoting dual transformation, policymakers in formulating relevant policies, and academics in conducting in-depth research.

(2) It reveals how digital technology affects the mechanism of enterprise green innovation. Previous studies mostly explored human resource allocation from the perspective of natural resources (Liu et al., 2024; Zhao & Qian, 2023) and the role of enterprise R&D capability (Feng et al., 2022) and financial capability (Yang & Sun, 2023) in the process of digital technology affecting enterprise green innovation. However, green innovation often has the characteristics of high risk and high investment, and there are often serious problems of information asymmetry, which leads to low efficiency (Wang & Zhong, 2024), so capital acquisition and information integration are particularly important. Therefore, taking "financing constraint" and "information constraint" as mechanism variables, this paper deepens our understanding of the essence of the relationship between digital technology and enterprise green innovation.

(3) The heterogeneity of green innovation effect of digital technology is analyzed. Some studies only studied the different effects of different environmental factors on the green innovation effect of digital technology (He et al., 2024), and the conclusion may be more one-sided; under different external environments and enterprise attributes, the impact of digitalization on green innovation may be asymmetric (Wang & Zhong, 2024). This paper considers the possible heterogeneous effects among enterprises under different property rights, different pollution levels, and different regional economic development levels, and provides some basis for relevant parties to make wiser and more targeted decisions and strategies.

*2.3. Research framework and approach*

With the development of big data text mining technology, it is worth exploring how to deal with the difficulties in micro-level indicator measurement of digital technology. This paper collected annual reports of Chinese listed companies on the Shanghai and Shenzhen stock exchanges from 2010 to 2021 through Python web crawling, and then constructed enterprise-level indicators of digital technology proficiency using text mining technology. The impact and mechanism of digital technology on corporate green innovation are examined from both qualitative and quantitative perspectives. The specific research framework is illustrated in Figure 1.

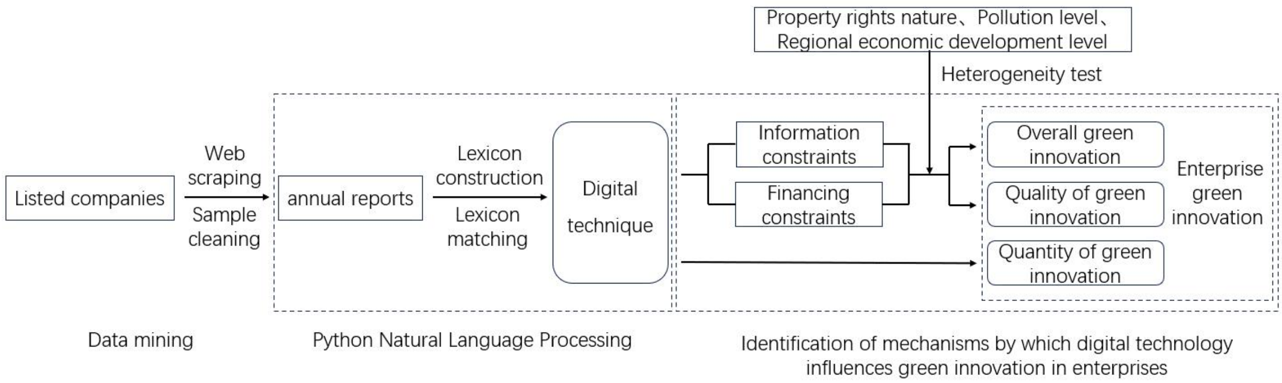

**Figure 1.** Research framework of this paper.

## 3. Quantitative test of the impact of digital technology on enterprise green innovation

### *3.1. Model construction of the impact of digital technology on enterprise green innovation*

Digital technology as a profound impact on enterprise green innovation behavior. Digital technology refers to information, computation, communication, and connectivity technologies and their combinations, including artificial intelligence, big data, cloud computing, and blockchain (Vial, 2019). As the technical support of the digital economy, it has profoundly changed various aspects of society and the economy, playing a positive role in green development (Xu et al., 2022), and has become one of the core elements promoting China's economic development. First, digital technology helps to improve the input–output efficiency of enterprise green innovation. From that perspective, digital technology has the ability to drive traditional production modes characterized by high input, high output, high energy consumption, and high pollution to low-carbon, energy-saving, and efficient production modes (Li et al., 2023). Under the incentive of digital technology, enterprises can generate more redundant resources, moving toward long-term returns and being willing to invest more resources in green innovation activities. Meanwhile, enterprises pay increasing attention to ecological safety to minimize environmental impacts while ensuring the production of eco-friendly products (Keswani & Khedlekar, 2024). Digital technology can help enterprises achieve refined production management, green supply chain management, energy management, and emission reduction, reducing marginal transaction costs for enterprises and resulting in more green outputs. For example, using machine learning with artificial intelligence can help to monitor and analyze production data in real-time, optimize production processes, assess and manage environmental risks in the supply chain, and reduce energy consumption and waste emissions, thus improving output capacity. Second, digital technology helps enhance enterprise R&D capabilities for green innovation. On the one hand, digital technology innovation and application can effectively promote the optimization of enterprise production and operation processes and the efficiency of resource allocation (Wang et al., 2021). By utilizing big data and artificial intelligence technology, enterprises can conduct in-depth data analysis of production and operation processes, optimize processes, eliminate waste, predict future trends and demands, and better adjust resource allocation and production planning, thereby improving R&D efficiency and resource utilization efficiency for enterprise green innovation. On the other hand, the application of digital technology promotes information flow and sharing within enterprises. Internally, digital technology can strengthen communication among different individuals or departments within enterprises, reduce information silos within enterprises, promote information flow and resource sharing among departments (Liu & Chen, 2022), improve employee work efficiency, and thereby enhance R&D capabilities. For example, enterprises can use various databases and cloud storage solutions to integrate their information and ensure it is accessible and shareable, and employees can communicate and share information in real-time through email, instant messaging, and other online collaboration tools.

Digital technology has different effects on the green innovation behavior of different enterprises.

Enterprise green innovation is divided into strategic and substantive innovation. Li and Zheng (2016) believed that the increase in innovation "quantity" for the sake of obtaining government support and seeking external legitimacy is only a strategic innovation rather than substantive innovation. Only an increase in the number of invention patents can enhance the market value of enterprises, and "high-quality" substantive innovation is the source of enterprise value. On the one hand, enterprises tend to respond positively by rapidly increasing the "quantity" and "speed" of green innovation to obtain specific subsidies and policy benefits and to seek external legitimacy (Wu et al., 2022). Their increase is more about obtaining specific subsidies and policy benefits rather than seeking technological progress or product upgrades. Therefore, the resulting green utility model patents often have simple and one-sided characteristics. However, the realization process of digital technology is often difficult, and the resulting outcomes are relatively complex, comprehensive, and high-quality. Therefore, the impact of digital technology on the strategic innovation behavior of enterprises may not be significant. On the other hand, digital technology itself is a scientific and technological progress that brings innovative ways (Hilbert, 2020), while green invention patents have characteristics such as innovation, environmental protection, feasibility, and economy. Digital technology plays an important role in improving substantive enterprise green innovation. For example, in supply chain management, blockchain technology can record information at every link, including the source of raw materials, processing, transportation, and sales, thereby tracing environmental issues that may exist in the entire production process and addressing them promptly; a machine learning-based technology innovation performance prediction method can help improve the performance of enterprise technological innovation and improve the convenience of electronic commerce (Zhang et al., 2023). Digital technology fundamentally changes the current situation of enterprise production and operation, promotes enterprises to achieve digitalization, intelligence, platformization, and greenization in various aspects, and has become the most innovative, widely applicable, and influential technological innovation field, profoundly affecting the green innovation behavior of enterprises.

This paper studies the impact of digital technology on enterprise green innovation, and sets the benchmark estimation model as follows:

$$GI_{it} = \alpha_0 + \alpha_1 Digtec_{it} + \alpha_2 Control_{it} + \delta_i + \mu_t + \varepsilon_{it} \quad (1)$$

where $GI_{it}$ represents the enterprise green innovation index of the $i$ enterprise in year $t$, the core explanatory variable $Digtec_{it}$ represents the enterprise digital technology level index, $Control_{it}$ is a set of control variables, including enterprise size, capital intensity, human capital, and enterprise maturity, $\delta_i$ represents individual fixed effects, $\mu_t$ represents year fixed effects, and $\varepsilon_{it}$ represents the random error term.

### *3.2. Data processing and variable selection*

#### 3.2.1. Data source and processing

The research sample of this paper consists of Chinese listed companies on the Shanghai and Shenzhen stock exchanges from 2010 to 2021. The research data was processed as follows. (1) Exclusion of ST-type samples; (2) exclusion of financial insurance companies; (3) exclusion of samples with severe missing data for the main research variables; (4) exclusion of samples with outliers. The annual reports of companies were obtained from the official website of the Shanghai and Shenzhen stock exchanges, while green patent data were sourced from the China Research Data Service Platform (CNRDS), human capital data from the WIND database, regional economic development level data from the National Bureau of Statistics, and other variable data from the CSMAR database.

### 3.2.2. Variable selection

(1) Explanatory variables

The core explanatory variable of interest in this paper is digital technology. The three main features of digital technology are (1) any digital device can store, convert, transmit, and track homogenized digital information; (2) digital technology allows digital information to be transformed through reprogramming, thereby rapidly adjusting to changes in application scenarios; (3) the self-referential nature of digital technology, i.e., the production of digital technology, requires support from previous digital technology (Tao et al., 2023), indicating that the measurement of digital technology cannot be separated from various data elements. Therefore, following the approach of Tang et al. (2022), this paper uses the Enterprise Data Element Development and Utilization Index to characterize digital technology, reflecting its overall picture and complexity. The vocabulary usage in annual reports can reflect the strategic characteristics and future prospects of enterprises, largely reflecting the management philosophy advocated by enterprises and the development path guided by this philosophy. In the current era, digital technology is regarded as a key tool for enterprises to achieve high-quality development, and such important information is often highlighted in the annual summaries and guiding annual reports of enterprises. Therefore, based on natural language processing through big data text mining to measure digital technology, a digital technology text mining dictionary was constructed, which includes data element stock, data development capabilities, data-driven business applications, and data value realization (Table 1). The specific technical implementation process is as follows:

- Crawling of enterprise annual report data: (1) Using the Python programming language, call libraries such as requests to implement web crawling. The stock code, company name, year, full name of the annual report, download link, and other field information were fetched from the official website of the Shanghai and Shenzhen stock exchanges to generate a preliminary Excel list, totaling 243,751 rows of data. (2) Initial data cleaning was performed by selecting data with years between 2010 and 2021 and excluding data with invalid keywords such as "abstract," "mid-term," "English," "half-year," "canceled," etc., in the full name of the annual report. After the initial filtering, there were still a few pieces of information unrelated to the enterprise annual reports, which were manually filtered to obtain 38,723 rows of valid data. (3) The corresponding annual report PDFs were downloaded using a loop traversal method for future use.
- Construction of digital technology indicators: (1) Using Python to call the fitz library to identify images, text, and other content in annual reports, forming a textual data source for subsequent feature word selection. (2) Using Python to call the jieba library for word segmentation processing of the textual content in annual reports, generating a Chinese word segmentation database. (3) The words covered in the dictionary (Table 1) were searched, matched, and counted to obtain their weight in the total word frequency, which served as the measurement index of digital technology (Digtec). The

calculation formula can be constructed as follows:

$$Digtec_{it} = \frac{\sum_{s=1}^{N_{it}} I\,(W_s \in Dictionary)}{N_{it}} \tag{2}$$

where $Digtec_{it}$ represents the digital technology level index of the $i$ enterprise in year $t$, and $I$ is the indicator function, which returns 1 when the condition is satisfied and 0 otherwise. $W_s$ represents the Chinese word after word segmentation. $Dictionary$ represents the keyword set of the data element development and utilization index. $N_{it}$ represents the total number of Chinese word segments in the annual report of the $i$ enterprise in year $t$ after word segmentation processing.

**Table 1.** Selection of key terms for digital technology and construction of dictionary.

| Dimension | Index of data element development and utilization keywords |
|---|---|
| Data element stock | Big Data, Data Integration, Data Fusion, Data Information, Data Management, Data Assets, Digitization |
| Data development capability | Automation, 5G, Intelligence, Robotics, Machine Learning, 3D Printing, 3D Technology, 3D Tools, AI (Artificial Intelligence), Internet of Things (IoT), Edge Computing, Cloud Computing, Cloud Services, Cloud-based, Digital Science, Digital Technology, Computer Technology, Information Age, Informatization, Information Technology, Information Integration, Information Communication |
| Data-driven business applications | O2O (Online-to-Offline), B2B (Business-to-Business), C2C (Consumer-to-Consumer), P2P (Peer-to-Peer), C2B (Consumer-to-Business), B2C (Business-to-Consumer), Electronic Technology, Electronic Science and Technology, Online, Internet, Online and Offline, Internet, E-commerce, Cross-border E-commerce, E-commerce Platform, Smart Era, Smart Construction, Smart Business, Digital Operations, Digital Terminals, Digital Economy, Digital System, Digital Supply Chain, Digital Marketing |
| Data value realization | Digital Currency, Blockchain, Digital Trade |

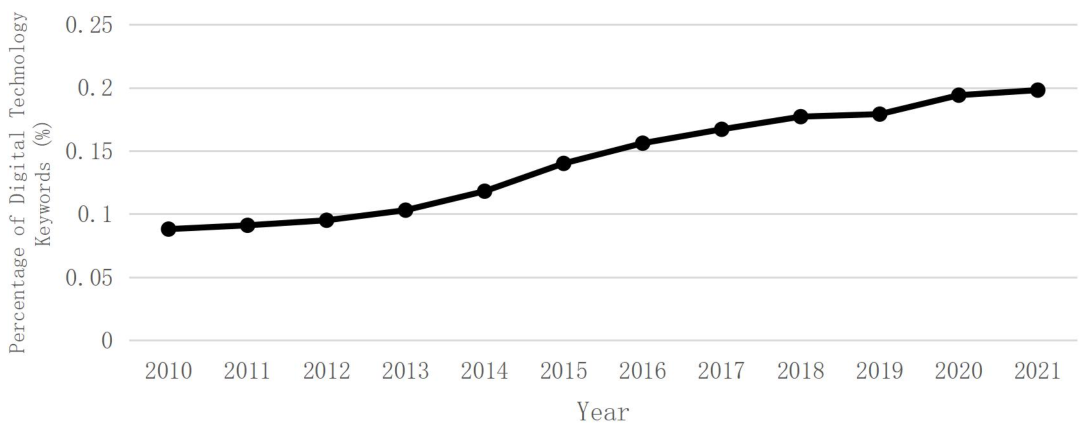


**Figure 2.** Trend chart of digital technology index for listed companies in Shanghai and Shenzhen stock exchanges, China, 2010–2021.

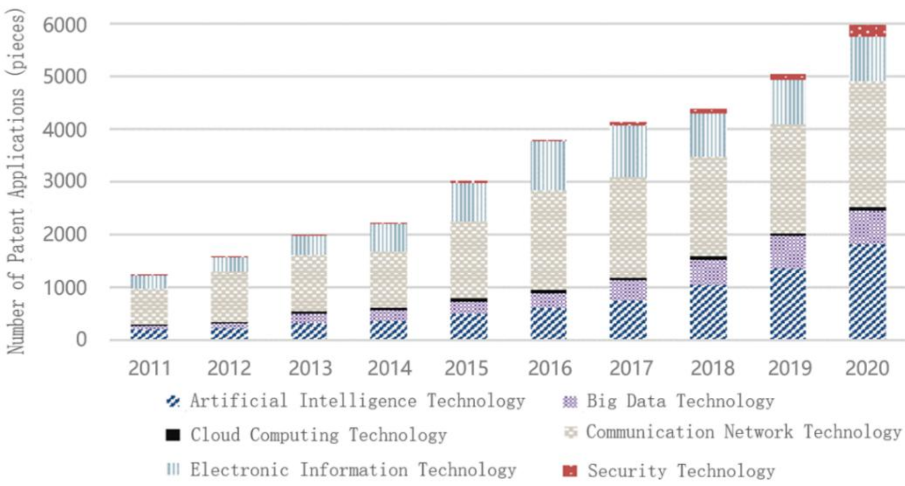


**Figure 3.** Digital patent application situation of A-share listed companies in Shanghai and Shenzhen, China, 2011–2020.[1]

Figure 2 presents the annual trend of the digital technology index for listed companies in Shanghai and Shenzhen, China. Zhou et al. (2024) utilized data from A-share listed companies in Shanghai and Shenzhen from 2011 to 2020 and used the number of digital patent applications to measure digital technology innovation. Comparing the digital technology index (Digtec) constructed in this paper with the number of digital patent applications, it is evident that the sample's level of digital technology exhibits similar characteristics, showing an increasing trend year by year. This aligns with the overarching trend in the digital economy, where data serves as a crucial production factor and digital technology acts as a core driving force. It also ensures that the Digtec index constructed in this paper effectively measures the level of digital technology of enterprises, laying the foundation for subsequent empirical tests of the impact and mechanisms of digital technology on enterprise green innovation.

(2) Dependent variable

This study focuses on enterprise green innovation as the dependent variable. Currently, there is a vast amount of literature discussing measurement methods for enterprise green innovation, with many scholars using R&D investment and patent grants as metrics. First, enterprise R&D investment mainly measures the pre-investment of resources before innovation activities, which does not necessarily represent the output of innovation activities. Conversely, patent grants require detection and payment of annual fees, and government subsidies for patents encompass application, examination, authorization, maintenance, and patent agency services. If the government focuses on encouraging an increase in patent grants, it may enhance subsidies for the patent authorization process, potentially influenced by bureaucratic factors (Lian et al., 2022). Therefore, following the approach of Li and Zheng (2016), this study employs the number of green patent applications by listed companies to measure enterprise green innovation. Specifically, the sample company's information on invention patent applications and utility model patent applications is obtained from the China Research Data Service Platform (CNRDS) and then matched according to the International Patent Classification Green List published by the World

[1] Figure 3 from Zhou et al. (2024), see the website of China Industrial Economy (http://ciejournal.ajcass.org), Attachment Download.

Intellectual Property Organization (WIPO). The final count represents the number of enterprise green patent applications. The total number of green patent applications is used to measure the overall level of enterprise green innovation (total), further decomposed into the number of green invention patent applications and the number of green utility model patent applications, measuring the quality (invention) and quantity (utility) of enterprise green innovation. Additionally, the green patent data are transformed by adding 1 and taking the natural logarithm as the final indicator.

(3) Control variables

Drawing from the studies of Xu and Cui (2020) and Li and Xiao (2020), the following control variables are selected: enterprise size (size), measured by the natural logarithm of total assets; enterprise maturity (age), measured by the years of operation; capital intensity (density), measured by the ratio of total assets to operating income; and human capital (capital), measured by the proportion of employees with a college degree or above to the total number of employees.

### *3.3. Descriptive statistics*

The descriptive statistics of the main variables in this study are presented in Table 2. The range of the dependent variable enterprise green innovation (total, invention, and utility) is large, indicating significant differences in green innovation levels among different companies. The average value of digital technology (Digtec) is 0.001, with a standard deviation of 0.002. The minimum value is 0, and the maximum value is 0.02, suggesting that the overall deviation of digital technology levels in the sample is not significant. The standard deviation of enterprise maturity (age) is 6.289, indicating significant differences in the operating years of sample companies. The average value of human capital (capital) is 0.534, with a minimum of 0.233 and a maximum of 1.000, indicating a higher proportion of companies with high educational attainment in the sample. The range of values for capital intensity (density) is large, with the mean significantly smaller than the maximum value, indicating significant differences in production methods and financing needs among sample companies. The average value of enterprise size (size) is 22.49, with a minimum of 18.680 and a maximum of 28.640, suggesting a higher number of small and medium-sized enterprises in the sample.

**Table 2.** Descriptive statistics.

| Variables | Observations | Mean | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Total | 11928 | 1.126 | 1.355 | 0.000 | 7.356 |
| Invention | 11928 | 0.795 | 1.157 | 0.000 | 7.231 |
| Utility | 11928 | 0.768 | 1.098 | 0.000 | 6.234 |
| Digtec | 11928 | 0.001 | 0.002 | 0.000 | 0.020 |
| Age | 11928 | 17.41 | 6.289 | 1.000 | 54.000 |
| Capital | 11928 | 0.534 | 0.233 | 0.004 | 1.000 |
| Density | 11928 | 2.461 | 3.558 | 0.088 | 155.900 |
| Size | 11928 | 22.49 | 1.430 | 18.680 | 28.640 |

### *3.4. Benchmark regression*

To explore the impact of digital technology on enterprise green innovation, this study first constructs a fixed effects model for empirical analysis. The results of the benchmark regression are presented in Table 3. In columns (1), (3), and (5), individual fixed effects are controlled without controlling for year effects. In columns (2), (4), and (6), both year effects and individual fixed effects are controlled simultaneously.

**Table 3.** Benchmark regression.

| Variables | (1) Total | (2) Total | (3) Invention | (4) Invention | (5) Utility | (6) Utility |
|---|---|---|---|---|---|---|
| Digtec | 49.307*** | 44.900*** | 55.562*** | 52.977*** | 10.949 | 6.894 |
| | (12.573) | (12.145) | (12.705) | (12.586) | (10.047) | (9.718) |
| Age | 0.025*** | −0.004 | 0.018*** | 0.002 | 0.016*** | −0.012*** |
| | (0.005) | (0.004) | (0.004) | (0.004) | (0.004) | (0.004) |
| Capital | 0.435*** | 0.496*** | 0.536*** | 0.579*** | 0.251** | 0.304*** |
| | (0.136) | (0.135) | (0.124) | (0.123) | (0.113) | (0.113) |
| Density | −0.003 | −0.004 | −0.002 | −0.003 | −0.003 | −0.004* |
| | (0.002) | (0.003) | (0.002) | (0.002) | (0.002) | (0.002) |
| Size | 0.349*** | 0.292*** | 0.276*** | 0.236*** | 0.239*** | 0.191*** |
| | (0.032) | (0.032) | (0.029) | (0.028) | (0.027) | (0.027) |
| Constant term | −7.442*** | −5.932*** | −6.094*** | −5.082*** | −5.041*** | −3.714*** |
| | (0.660) | (0.658) | (0.594) | (0.592) | (0.566) | (0.563) |
| Individual fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed | No | Yes | No | Yes | No | Yes |
| N | 11928 | 11928 | 11928 | 11928 | 11928 | 11928 |
| Adjusted R-squared | 0.165 | 0.218 | 0.150 | 0.178 | 0.095 | 0.159 |

Note: Standard errors in parentheses; ***, **, and * denote significance levels of 1%, 5%, and 10%, respectively, throughout the tables below.

The results of the benchmark regression indicate that digital technology significantly enhances enterprises' green innovation capability but focuses more on "quality improvement over quantity". Regardless of considering the fixed effects of the year, the regression coefficients of the digital technology index (Digtec) in columns (1) to (4) are all significantly positive at the 1% level, indicating that digital technology significantly enhances both the overall level and the quality of enterprises' green innovation. However, the regression coefficients of the digital technology index (Digtec) in columns (5) to (6) are not significant, suggesting that digital technology has no significant impact on the quantity of enterprises' green innovation. On the one hand, the realization of digital technology often requires long-term technological accumulation and substantial investment of manpower and material and financial resources, which can bring high-quality green innovation to enterprises, fundamentally improving their competitiveness and sense of social responsibility in green technology. On the other hand, based on objective economic facts, most Chinese firms respond to environmental laws and regulations by imitating or engaging in low-quality innovation to quickly obtain short-term government support (Lian et al., 2022), focusing solely on increasing innovation quantity without deep integration with digital technology. These results imply that in the digital economy era, digital technology primarily brings about a qualitative improvement in product and service quality for firms, rather than being merely a tool to pursue policy dividends. It has become an important driver for promoting enterprises' green innovation and enhancing market competitiveness.

### 3.5. Robustness tests

To further validate the reliability of the empirical results, we conducted the following robustness tests. First, we conducted regressions with the lag of one period (L1.Digtec) and two periods (L2.Digtec) of digital technology (Digtec) to address potential endogeneity issues. Second, considering that there may be differences in the application of digital technology and environmental regulation policies among regions with different levels of economic development, industries with varying pollution levels, and different years, we controlled for the high-level joint fixed effects of region-year and industry-year on the basis of the benchmark regression. This, to some extent, mitigates the impact of changes in the macro-systemic environment on the regression results (Wang & Zhong, 2024). In Table 4, columns (1)–(3) represent the regression results of digital technology with a lag of one period (L1.Digtec), columns (4)–(6) represent the regression results of digital technology with a lag of two periods (L2.Digtec), and columns (7)–(9) represent the regression results with the control of region-year and industry-year high-level joint fixed effects. The results shown in Table 4 are consistent with the benchmark regression results. Digital technology significantly enhances a firm's green innovation capabilities, but it does so by "improving quality without increasing quantity", thereby confirming the validity of the research findings presented in this article.

**Table 4.** Robustness test results.

| Variables | (1) Total | (2) Invention | (3) Utility | (4) Total | (5) Invention | (6) Utility | (7) Total | (8) Invention | (9) Utility |
|---|---|---|---|---|---|---|---|---|---|
| L1.Digtec | 49.103*** | 55.840*** | 6.513 | | | | | | |
| | (12.508) | (12.757) | (9.508) | | | | | | |
| L2.Digtec | | | | 32.544** | 40.469*** | −5.992 | | | |
| | | | | (13.087) | (12.768) | (9.612) | | | |
| Digtec | | | | | | | 47.950*** | 51.500*** | 11.874 |
| | | | | | | | (7.551) | (6.732) | (6.544) |
| Control Variables | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Region-year fixed | No | No | No | No | No | No | Yes | Yes | Yes |
| Industry-year fixed | No | No | No | No | No | No | Yes | Yes | Yes |
| N | 10934 | 10934 | 10934 | 9940 | 9940 | 9940 | 11928 | 11928 | 11928 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Adjusted R-squared | 0.198 | 0.159 | 0.147 | 0.176 | 0.136 | 0.136 | 0.754 | 0.732 | 0.719 |

## 4. Mechanism analysis of the impact of digital technology on enterprise green innovation

### *4.1. Model construction of the mechanism of digital technology's impact on enterprise green innovation*

Digital technology can effectively alleviate financing constraints and assist enterprises in conducting green innovation activities. Financing constraints refer to limitations or obstacles in obtaining funds faced by enterprises, which vary at different stages of their development. Green innovation activities of enterprises typically involve high risks, multidisciplinary intersections, and a sustainability orientation, with high technological difficulty and long investment return cycles. Insufficient and irregular inflow of funds often leads to inadequate research and development (R&D) investment, affecting innovation outputs (Hall & Lerner, 2010). For small and medium-sized enterprises (SMEs), digital technology facilitates the diversification of financing channels to raise funds for green innovation activities. On the one hand, digital technology can signal positively to attract external investors, bringing market resources for enterprise green innovation. The process of enterprise digital transformation strategy can be seen as a proactive response to the national economic policy orientation, demonstrating the maintenance of a good relationship among enterprises, government, and the market (Nosova et al., 2021). Investment institutions have made significant efforts to adjust their operations and incorporate sustainable indicators into the market (Matallín-Sáez & Soler-Domínguez, 2023). From investors' perspectives, enterprises that engage in R&D and innovation in encouraged areas by the government and launch products and technologies that meet market demand are likely to receive government support and preferential policies, thereby promoting innovation (Wang et al., 2017). On the other hand, the development and application of digital technology have given rise to new financing models. Compared to traditional financing models, emerging financing models such as crowdfunding, blockchain financing, digital currency, and cryptocurrency financing provide diversified options for enterprises, reduce financing barriers, and attract and integrate more funds to support green technology innovation activities. Furthermore, the application of deep learning neural network algorithms can effectively evaluate market risks and resource allocation capabilities in green credit businesses (He et al., 2022). Although substantial financial investment is a fundamental condition for improving the level of green innovation in enterprises, for large-scale enterprises, due to their complex operational environment, the improvement of the financing environment may not completely address the challenges they face in conducting green innovation activities. For example, Tesla's large-scale transformation in the electric vehicle field requires substantial funding for R&D and production of new electric vehicles, including updating production line equipment, developing battery technology, and constructing charging infrastructure. Although financial investment plays an important role in it, the transformation involves not only technology and production but also complexity in market acceptance, government regulation, environmental regulations, and industry cooperation, and alleviating financing constraints alone may not solve the entire challenge of green innovation.

Digital technology can effectively alleviate information constraints and enhance enterprises' green innovation capabilities. Information constraints refer to limitations caused by incomplete or insufficient information to support effective decision-making. Incomplete or asymmetric information hinders enterprises' insight into environmental trends, understanding of market demand, and limited access to innovation resources and information communication channels. Enterprises can utilize advanced digital technology to identify and access more online resources, break through information silos, grasp market development trends and consumer demands, and accelerate the formation of green ideas while forming a resource network. On the one hand, digital technology helps enhance information exchange and transparency between enterprises and external stakeholders. The application of digital technology helps enterprises reorganize and plan product, process, resource, and external environmental information, effectively addressing issues such as departmentalization, fragmentation, and information asymmetry, forming a complete data information system, assisting enterprises in making scientifically-based decisions beneficial to economic efficiency and environmental protection (Xue et al., 2022). For example, digital finance relies on modern digital technologies such as big data, blockchain, and artificial intelligence to alleviate information asymmetry in traditional financial transactions, promote the financing of high-quality innovation projects, and thereby promote innovation development (Li et al., 2023). On the other hand, digital technology helps investors comprehensively evaluate the sustainability and value of enterprises' green innovation activities, reducing the risks of information asymmetry. High-quality information is the primary basis for investor decision-making (Chen et al., 2024). Digital technology allows enterprises to disclose environmental protection and sustainable development information more comprehensively in digital reporting formats and online platforms, such as their environmental goals, action plans, reports, and achievements. This may spark investor interest in new environmental projects, provide them with more choices, and increase portfolio diversity. More importantly, digital platforms enable investors to obtain enterprise information from multiple channels, including financial data, market conditions, and environmental and social impacts, efficiently integrate large amounts of data for analysis, promote rapid matching of information between investors and enterprises, enhance investors' confidence and willingness to invest, and provide sufficient financial support for enhancing enterprises' green innovation capabilities.

Based on this, information constraints and financing constraints may be two channels through which digital technology affects enterprise green innovation. To empirically identify them, referring to the literature of Zhang et al. (2021), this paper constructs the following model for testing:

$$Restrain_{it} = \alpha_0 + \alpha_1 Digtec_{it} + \alpha_2 Control_{it} + \delta_i + \mu_t + \varepsilon_{it} \tag{3}$$

where $Restrain_{it}$ represents the mechanism variable being tested, which includes financing constraints and information constraints. The widely used methods for measuring financing constraints in academia include the KZ index, WW index, SA index, and FC index. In this paper, following the methodology of Yu et al. (2021), the FC index is used to measure the degree of financing constraints faced by companies. It establishes a model to fit the probability of financing constraints occurring in each year, denoted as P, and defines it as the financing constraint index FC. The larger the FC, the more severe the company's financing constraint problem. Information constraints mainly manifest as information asymmetry, but since information asymmetry is difficult to directly observe and measure, this paper refers to the research of Ding et al. (2021) and uses the stock bid-ask spread (Stobuy) to measure the degree of information constraints in companies. If there is no information asymmetry, the bid-ask spread is zero; otherwise, if information asymmetry exists, the bid-ask spread should increase. The FC index data and stock bid-ask spread data used in this paper are from the CSMAR database.

### *4.2. Mechanism analysis of the impact of digital technology on overall enterprise green innovation level*

#### 4.2.1. Financing constraints

This paper first examines the mechanism of how digital technology affects the overall level of enterprise green innovation based on financing constraints, including all samples in the test scope. The results of the mechanism test are shown in Table 5.

**Table 5.** Identification of the mechanism of digital technology's impact on overall enterprise green innovation level under the full sample: financing constraints.

| Variables | (1)<br>Total | (2)<br>FC | (3)<br>Total |
|---|---|---|---|
| Digtec | 44.900*** | −4.917*** | 44.383*** |
| | (12.145) | (1.619) | (12.159) |
| FC | | | −0.105 |
| | | | (0.088) |
| Control variables | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes |
| N | 11928 | 11928 | 11928 |
| Adjusted R-squared | 0.218 | 0.464 | 0.218 |

The results indicate that the estimated coefficient of FC in column (3) of Table 5 is not significant, suggesting that digital technology does not affect the overall level of enterprise green innovation through financing constraints. The improvement of overall enterprise green innovation level relies on continuous funding, and company size is an important factor influencing the degree of financing constraints (Czarnitzki & Hottenrott, 2011). Companies of different sizes may face differences in financing costs and difficulties, and the main factors affecting their own green innovation activities may also differ, leading to the conclusion that, overall, digital technology does not affect the overall level of enterprise green innovation through financing constraints.

Therefore, this study further subdivides the sample into small and medium-sized enterprises (SMEs) and large-scale enterprises (LSEs) and conducts separate regressions to explore whether the impact of digital technology on the overall level of enterprise green innovation through financing constraints is related to the size of the enterprise. The regression results are presented in Table 6.

**Table 6.** Identification of the mechanism of digital technology's impact on overall enterprise green innovation level under the sub-samples: financing constraints.

| Variables | Small and medium-sized enterprises | | | Large enterprises | | |
|---|---|---|---|---|---|---|
| | Total | FC | Total | Total | FC | Total |
| Digtec | 47.046*** | −3.820** | 46.206*** | 61.527 | −1.461 | 64.566 |
| | (11.248) | (1.658) | (11.249) | (82.678) | (1.601) | (82.962) |
| FC | | | −0.220** | | | 2.080 |
| | | | (0.088) | | | (1.287) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 10276 | 10276 | 10276 | 1652 | 1652 | 1652 |
| Adjusted R-squared | 0.197 | 0.469 | 0.198 | 0.301 | 0.389 | 0.303 |

The results show that digital technology enhances the overall green innovation level of small and medium-sized enterprises (SMEs) by alleviating financing constraints, with no effect on large-scale enterprises. For SMEs, the estimated coefficient of Digtec in column (2) is significantly negative, indicating that digital technology significantly alleviates financing constraints. Furthermore, the estimated coefficient of FC in column (3) is also significantly negative, indicating that the alleviation of financing constraints promotes the improvement of the overall green innovation level of enterprises. The coefficient of Digtec in column (3) is smaller than that in column (1), indicating the existence of the mechanism of financing constraints. However, for large-scale enterprises, the estimated coefficient of FC in column (6) is not significant, suggesting the absence of the mechanism of financing constraints. Financing difficulties are a primary factor restricting the survival and development of Chinese SMEs (Yao & Liu, 2018), and their internal funds are usually unstable and limited (Li & Wang, 2021). The application of digital technology provides SMEs with diversified financing channels. Through online financing platforms, digital banking services, or international financing platforms, SMEs can conveniently obtain financing, while also enhancing the effectiveness of digital financial risk control (Liao et al., 2022), thereby providing stable financial support for green innovation-related activities. For example, accurate prediction of corporate financial risks through neural network models can provide guidance for managers to avoid financial risks (Sun et al., 2023). Green innovation strategy is one of the most important ways for enterprises to achieve sustainable and long-term development (Du & Cao, 2023). With the expansion of enterprise scale, enterprises often pay more attention to green strategies, green market orientation, corporate reputation, and brand image, focusing on their own long-term development and stable market position, leading to various green innovation challenges, with the impact of financial aspects possibly significantly weakened.

### 4.2.2. Information constraints

Continuing based on information constraints, all samples are included for testing the mechanism by which digital technology influences the overall green innovation level of enterprises, and the test results are shown in Table 7.

**Table 7.** Identification of the mechanism of digital technology's impact on overall enterprise green innovation level under the full sample: information constraints.

| Variables | (1) Total | (2) Stobuy | (3) Total |
|---|---|---|---|
| Digtec | 44.900*** | −3.488*** | 43.381*** |
| | (12.145) | (1.112) | (12.130) |
| Stobuy | | | −0.435** |
| | | | (0.217) |
| Control variables | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes |
| N | 11928 | 11928 | 11928 |
| Adjusted R-squared | 0.218 | 0.196 | 0.218 |

The results indicate that digital technology enhances the overall green innovation level of enterprises by alleviating information constraints. The estimated coefficient of Digtec in column (2) of Table 7 is significantly negative, indicating that digital technology significantly alleviates information constraints. Furthermore, the estimated coefficient of Stobuy in column (3) is also significantly negative, indicating that the alleviation of information constraints promotes the improvement of the overall green innovation level of enterprises. The coefficient of Digtec in column (3) is smaller than that in column (1), suggesting the existence of the mechanism of information constraints. With the increasing penetration of environmental protection concepts, investors are increasingly incorporating companies' green practices into their investment decisions (Tsagkanos et al., 2022). Any information disclosure may affect the production and operation of enterprises (Li et al., 2021), and digital technology enables companies to transparently showcase their green innovation initiatives and environmental performance to external investors, helping external investors better evaluate environmental risks and opportunities, and enhancing corporate reputation and investor value recognition. In addition, regardless of the stage of development, digital technology always helps companies break information silos, providing optimization paths for information transmission and resource integration among different departments and institutions within companies, enabling companies to formulate more scientific and feasible green innovation strategies, thereby enhancing their willingness and ability to independently carry out green innovation.

*4.3. Mechanism analysis of digital technology's impact on the quality of enterprise green in-novation*

4.3.1. Financing constraints

The benchmark regression results indicate that technology significantly enhances enterprises' green innovation capability but focuses more on quality improvement over quantity. Therefore, based on financing constraints, all samples are included in the testing scope. This paper further examines the mechanism by which digital technology influences the quality of enterprise green innovation, and the results are shown in Table 8.

**Table 8.** Identification of the mechanism of digital technology's impact on the quality of enterprise green innovation under the full sample: financing constraints.

| Variables | (1)<br>Invention | (2)<br>FC | (3)<br>Invention |
|---|---|---|---|
| Digtec | 52.977*** | −4.917*** | 52.634*** |
| | (12.586) | (1.619) | (12.613) |
| FC | | | −0.070 |
| | | | (0.077) |
| Control variables | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes |
| N | 11928 | 11928 | 11928 |
| Adjusted R-squared | 0.178 | 0.464 | 0.178 |

The results indicate that the estimated coefficient of FC in column (3) of Table 8 is not significant, suggesting that digital technology does not affect the overall quality of enterprise green innovation through financing constraints. The substantial innovation behavior of enterprises is aimed at promoting technological progress and gaining competitive advantages (Li & Zheng, 2016). Different-sized enterprises may have significant differences in characteristics such as their cost of capital (Hong et al., 2023), innovation capabilities, innovation resources, and strategic planning. Therefore, when enterprises engage in high-quality green innovation activities to seek progress, the impact of external financing may vary, leading to an insignificant effect of financing constraints on the overall quality of related green innovation activities in society.

Hence, the sample is further divided into SMEs and large-scale enterprises, and regressions are conducted separately to explore whether digital technology affects the quality of enterprise green innovation through financing constraints related to the size of the enterprise. Regression results are presented in Table 9.

**Table 9.** Identification of the mechanism of digital technology's impact on the quality of enterprise green innovation under the sub-samples: financing constraints.

| Variables | Small and medium-sized enterprises | Large enterprises |
|---|---|---|

| | Invention | FC | Invention | Invention | FC | Invention |
|---|---|---|---|---|---|---|
| Digtec | 46.806*** | −3.820** | 46.068*** | 156.413* | −1.461 | 158.689* |
| | (10.595) | (1.658) | (10.601) | (84.445) | (1.601) | (84.469) |
| FC | | | −0.193*** | | | 1.559 |
| | | | (0.074) | | | (1.093) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 10276 | 10276 | 10276 | 1652 | 1652 | 1652 |
| Adjusted R-squared | 0.153 | 0.469 | 0.154 | 0.300 | 0.389 | 0.301 |

The results indicate that digital technology enhances the quality of green innovation for SMEs by alleviating financing constraints, with no significant effect on large-scale enterprises. For small-scale enterprises, the estimated coefficient of Digtec in column (2) is significantly negative, indicating that digital technology significantly alleviates financing constraints. Moreover, the estimated coefficient of FC in column (3) is significantly negative, indicating that the alleviation of financing constraints enhances the quality of green innovation. Additionally, the coefficient of Digtec in column (3) is smaller than that in column (1), suggesting the existence of the mechanism of financing constraints. However, for large-scale enterprises, the estimated coefficient of FC in column (6) is not significant, suggesting the absence of the mechanism of financing constraints. For SMEs, compared to conventional innovation, financing constraints have a more severe impact on green innovation, especially in the development of green invention patents and energy-saving patents (Albort-Morant et al., 2018). The development of green inventions and energy-saving technologies entails high uncertainty and risk, with high research and development costs and patent protection fees, which may be challenging for SMEs to bear. Indirect financing through financial intermediaries remains the primary channel for business in China (Yang et al., 2023), while digital technology provides SMEs with diversified, convenient, and flexible financing channels, helping them establish effective financial management systems and financial systems, effectively raise and manage funds, and support in-depth research in the field of green innovation. Large-scale enterprises typically possess strong capital strength, robust innovation capabilities, and more sophisticated strategic planning, allowing them to conduct high-precision technological breakthroughs without excessive reliance on short-term financing, thereby continuously advancing research on green innovation projects.

### 4.3.2. Information constraints

In addition, based on information constraints, this paper includes all samples in the test range to further examine the mechanism by which digital technology affects the quality of corporate green innovation, with the test results shown in Table 10.

**Table 10.** Identification of the mechanism of digital technology's impact on the quality of enterprise green innovation under the full sample: information constraints.

| Variables | (1)<br>Invention | (2)<br>Stobuy | (3)<br>Invention |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Digtec | 52.977*** | −3.488*** | 51.310*** |
| | (12.586) | (1.112) | (12.489) |
| Stobuy | | | −0.478** |
| | | | (0.191) |
| Control variables | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes |
| N | 11928 | 11928 | 11928 |
| Adjusted R-squared | 0.178 | 0.196 | 0.179 |

The results show that digital technology enhances the quality of corporate green innovation by alleviating information constraints. The estimated coefficient of Digtec in column (2) of Table 10 is significantly negative, indicating that digital technology significantly mitigates information constraints. Furthermore, the estimated coefficient of Stobuy in column (3) is significantly negative, suggesting that the alleviation of information constraints enhances the quality of corporate green innovation. The estimated coefficient of Digtec is also smaller than that in column (1), indicating the existence of the mechanism of information constraints. Information asymmetry affects business decisions and strategic processes (Li et al., 2024). In the context of increasing environmental regulations and public scrutiny of corporate environmental risks and behaviors, disclosing environmental and green innovation information by listed companies is not only a way to reduce environmental pollution but also a means to demonstrate corporate environmental management efforts and imply environmental risks (Bernardi & Stark, 2018). Digital technology can help companies release true information about green innovation activities, such as the quality of green patents and environmental benefits, which assists the government in accurately understanding corporate green innovation and reduces supervision costs, thereby increasing the likelihood of companies benefiting from green preferential policies and enhancing their confidence and motivation to carry out high-quality green innovation activities (Huang et al., 2019). Additionally, companies can use digital communication tools and neural networks to communicate with suppliers, partners, and consumers, enhancing communication and connection with external stakeholders, reducing delays and uncertainties in information transmission, accurately grasping market dynamics, and adjusting innovation strategies in a timely manner to ensure that R&D results meet market demands, fundamentally promoting corporate progress and competitiveness; for example, using neural networks to innovate design projects based on various green preferences of customers (Yang et al., 2019).

## 5. Heterogeneity analysis of the impact of digital technology on enterprise green innovation

### *5.1. Heterogeneity analysis considering property rights*

State-owned enterprises and private enterprises typically have significant differences in resource allocation and interest considerations. The level of environmental protection by local governments is an important factor affecting local enterprises' green innovation (Xie et al., 2017). In China, state-owned enterprises, due to their special political and economic status, may be more influenced by government policies and goals in their green innovation decisions. They typically place greater emphasis on social responsibility and long-term development and pay more attention to issues such as environmental protection and sustainable development. These factors may all affect the application of digital technology in green innovation. Therefore, to examine whether the green innovation effect of digital technology is influenced by property rights, this paper divides sample enterprises into state-owned and private enterprises based on their property rights attributes and conducts tests on the total amount, quality, and quantity of green innovation in each enterprise. The test results are shown in Table 11.

**Table 11.** Heterogeneous test considering property rights nature.

| Variables | Total | | Invention | | Utility | |
|---|---|---|---|---|---|---|
| | (1) Private enterprises | (2) State-owned enterprises | (3) Private enterprises | (4) State-owned enterprises | (5) Private enterprises | (6) State-owned enterprises |
| Digtec | 39.187*** | 88.364*** | 42.901*** | 113.528*** | 7.037 | 22.314 |
| | (12.965) | (29.113) | (12.135) | (34.816) | (10.969) | (21.016) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 7164 | 4764 | 7164 | 4764 | 7164 | 4764 |
| Adjusted R-squared | 0.210 | 0.247 | 0.166 | 0.224 | 0.157 | 0.170 |

Results indicate that the green innovation effect of digital technology is not influenced by the property rights nature of enterprises, but it is more pronounced in state-owned enterprises. The reason lies in the fact that the regression coefficients of Digtec in columns (1) to (4) are all significantly positive at the 1% significance level, and the regression coefficient of Digtec in state-owned enterprises is somewhat higher than that in private enterprises. Furthermore, columns (5) and (6) show that the regression coefficient of Digtec is not significant, indicating that digital technology has no significant impact on the quantity of green innovation in enterprises. Digital transformation has become an inevitable path for the survival and development of enterprises, and green production is also a general trend (Gao et al., 2023). Faced with increasingly severe environmental problems and resource constraints, both state-owned and private enterprises must actively embrace digital technology to achieve intelligence, automation, and refinement in various aspects such as production, management, and marketing. This is essential to minimize resource waste and environmental pollution in the green innovation process, achieving economic, social, and environmental benefits simultaneously. Additionally, compared to private enterprises, state-owned enterprises play a crucial role in the national economy and bear more responsibilities in ecological civilization construction. The state imposes relatively higher requirements on their green innovation and provides more policy, financial, and innovation resource support, thus creating a favorable environment for their green research and development innovation.

*5.2. Heterogeneity analysis considering pollution levels*

The green innovation activities of enterprises are also influenced by the characteristics of the industry in which they operate. Heavy pollution industries are typically concentrated in specific fields such as chemicals, mining, and energy. Their production processes and technological requirements differ significantly from those of non-heavy pollution industries, leading to higher difficulty and cost in upgrading and transforming their technologies. Furthermore, with the development of big data, the focus of innovation for heavy pollution industry enterprises is shifting toward non-green innovation, which in turn hinders the improvement of the quality of green innovation (Du et al., 2021). Therefore, to explore whether there are differences in the green innovation effect of digital technology among enterprises in industries with different pollution levels, this paper divides enterprises into two sub-samples according to their pollution levels: non-heavy-polluting and heavy-polluting. Tests are conducted on the total amount, quality, and quantity of green innovation in each enterprise, and the test results are presented in Table 12.

**Table 12.** Heterogeneity test considering pollution levels.

| Variables | Total | | Invention | | Utility | |
|---|---|---|---|---|---|---|
| | (1) Non-heavy pollution | (2) Heavy pollution | (3) Non-heavy pollution | (4) Heavy pollution | (5) Non-heavy pollution | (6) Heavy pollution |
| Digtec | 46.629*** | 6.653 | 47.437*** | 50.075 | 11.077 | −19.012 |
| | (13.070) | (33.200) | (12.994) | (57.551) | (10.479) | (27.519) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 8664 | 3264 | 8664 | 3264 | 8664 | 3264 |
| Adjusted R-squared | 0.230 | 0.187 | 0.198 | 0.120 | 0.159 | 0.165 |

The results indicate that compared to industries with heavy pollution, the role of digital technology in promoting overall green innovation levels and quality in industries with light pollution is more significant. The regression coefficients for light pollution industries in columns (1) to (4) of Table 12 are all significantly positive at the 1% level, whereas the coefficients for heavy pollution industries are not significant. Additionally, columns (5) and (6) show that the regression coefficients for Digtec are not significant, indicating that digital technology has no significant effect on the quantity of green innovation in enterprises. There are significant differences in the environmental impact of production and operation among different industries (Chen et al., 2021). Heavy pollution industries are often traditional heavy industrial sectors and major sources of pollution (Wang et al., 2021). Their production processes are usually highly customized, and they may be subject to stricter emission standards and pollution control requirements from the government, making the introduction of new green technologies require significant investment costs and facing resistance to application and promotion. In contrast, industries with light pollution are more involved in modern service industries and technological innovation, and often operate in rapidly changing market environments, requiring timely adjustments to adapt to new environmental standards and market trends. Digital technology provides tools such as real-time data analysis and intelligent decision support, aggregating fragmented demand and supply information, enabling enterprises in industries with light pollution to respond more quickly to issues such as energy efficiency, waste management, and sustainable supply chains, adjust their operating methods, meet evolving environmental requirements, and develop unique competitive advantages (Cheng et al., 2024).

### *5.3. Heterogeneity analysis considering regional economic development levels*

The level of regional economic development affects the resource conditions and future development space of enterprises. Different levels of regional economic development imply that enterprises may have significantly different production models and technological gaps (Hu, 2021; Su et al., 2022). Enterprises in regions with lower levels of economic development may face greater development pressure, technological gaps, and market demands. The application of digital technology may become an important means for these enterprises to enhance their green innovation capabilities. Therefore, to explore whether there are differences in the green innovation effects of digital technology among enterprises in regions with different levels of economic development, this paper divides the sample into three sub-samples based on the regional economic development levels: low development, medium development, and high development areas, and conducts tests on the total amount, quality, and quantity of green innovation in enterprises. The test results are shown in Table 13.

**Table 13.** Heterogeneity test considering regional economic development levels.

| Variables | Total | | | Invention | | | Utility | | |
|---|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
| | Low | Medium | High | Low | Medium | High | Low | Medium | High |
| Digtec | 42.805* | 56.514*** | 39.284 | 69.183** | 56.017*** | 42.517 | 8.538 | 19.383 | −11.718 |
| | (23.786) | (16.913) | (27.142) | (27.250) | (17.376) | (25.781) | (19.769) | (13.482) | (20.451) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Individual fixed | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Year fixed | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| N | 4260 | 5208 | 2460 | 4260 | 5208 | 2460 | 4260 | 5208 | 2460 |
| Adjusted | 0.223 | 0.214 | 0.224 | 0.175 | 0.176 | 0.193 | 0.157 | 0.165 | 0.163 |

| R-squared |
|---|

The results indicate that compared to enterprises located in regions with high levels of economic development, digital technology has a more significant impact on enhancing the overall level and quality of green innovation for enterprises in regions with moderate to low levels of economic development. The regression coefficients for low and moderate development in Table 13, columns (1) to (6), are all significantly positive, while those for high development are not significant. Additionally, columns (7) to (9) all show that the regression coefficients for Digtec are not significant, indicating that digital technology has no significant impact on the quantity of green innovation by enterprises. In contrast to enterprises located in regions with high levels of economic development, those in regions with moderate to low levels often face relatively backward levels of technology and management. Moreover, their regions may have disadvantages such as relatively single industrial structures, limited resource allocations, and insufficient market demand. Digital technologies such as big data and artificial intelligence can better integrate data elements into the production process, reducing reliance on traditional factors such as labor and thereby reducing production costs per unit output (Yin et al., 2022). This helps in reducing costs like labor, inventory management, and production wastage, narrowing the digital divide and bringing more equitable digital opportunities and comprehensive development to the regional economy. Meanwhile, regions with high levels of economic development generally have leading industrial structures, policy support, and societal awareness. Local enterprises typically possess a strong technological foundation and may have already invested in and implemented environmental protection technologies. Therefore, the application of digital technology may not lead to significant technological leaps or improvements in the level of green innovation in such regions.

## 6. Conclusion and policy recommendations

This study employs text mining techniques to extract relevant keywords related to digital technology from the annual reports of listed companies using Python. It constructs an indicator of digital technology level at the enterprise level and examines the impact and mechanism of digital technology on enterprise green innovation from the perspectives of quality and quantity. The research findings are as follows:

(1) Digital technology significantly enhances the overall level and quality of green innovation in enterprises but has no significant impact on the quantity of green innovation.

(2) Financing constraints and information constraints are two mechanisms through which digital technology affects enterprise green innovation. Specifically, digital technology can enhance the overall level and quality of green innovation in enterprises by alleviating financing constraints and information constraints, with the former affecting only SMEs.

(3) Heterogeneity analysis indicates that the green innovation effect of digital technology is not influenced by the property rights nature of enterprises but is more pronounced in state-owned enterprises. Moreover, the impact of digital technology on the overall level and quality of green innovation in non-heavy pollution industries is significantly higher than that in heavy pollution industries. Similarly, the effect of digital technology on the overall level and quality of green innovation in enterprises located in regions with moderate to low levels of economic development is significantly higher than that in regions with high levels of economic development.

Based on the above research conclusions, the following policy implications are derived. First, correctly guide and encourage enterprises to enhance their R&D and application capabilities of digital technology. Currently, the application of digital technology profoundly influences enterprises' behavior in green innovation, which is beneficial for improving the efficiency of green innovation investment and the R&D capability of enterprises. However, some enterprises solely pursue the speed and volume of green innovation to obtain more specific government subsidies and tax incentives, neglecting the essence of enhancing their own green innovation capabilities and market value. This study finds that digital technology has a significant impact on enterprise green innovation but has no significant effect on the quantity of green innovation. Therefore, the government should encourage enterprises to actively engage in digital innovation through policies, support their participation in environmental research projects, and guide them to focus on cultivating talents with green innovation awareness and skills to improve the efficiency and sustainability of green innovation. Additionally, when providing policy subsidies later, the government should specify the outcomes of enterprise green innovation, discerning based on difficulty, technological content, and value, to guide enterprises to focus on improving innovation capabilities and quality, achieving significant progress.

Second, emphasize the critical role of digital technology in alleviating financing constraints and information constraints. The relationship between digital technology and enterprise green innovation is not solely direct; this study finds that financing constraints and information constraints are vital mechanisms through which digital technology influences enterprise green innovation, with the former affecting only SMEs. Therefore, the government can develop financial products and services specifically designed for SMEs, including microloans, financing guarantees, and credit insurance, to meet their diverse financing needs. Additionally, reducing the tax burden on SMEs, simplifying financing procedures, and reducing financing approval time can improve the convenience of financing for SMEs. Furthermore, the government can invest in and promote the construction of digital infrastructure to help enterprises achieve efficient information sharing, break information silos, and promote the rapid development of green industries. Simultaneously, it should further improve and strengthen the disclosure system of capital markets to ensure the authenticity, accuracy, and completeness of information disclosure, enhancing the efficiency and quality of investor access to information, and helping enterprises attract more funds to promote the R&D and application of new green technologies.

Third, implement policies based on actual conditions to ensure the feasibility and targeting of policies. This study finds that the *quality improvement without quantity increase* effect of digital technology on enterprise green innovation exhibits heterogeneity due to differences in property rights, pollution levels, and regional economic development levels. Therefore, the government should fully consider the heterogeneity of enterprises when formulating relevant policies; for example, by developing digitalization subsidies and subsidy policies specifically for private enterprises to conduct green innovation, thereby reducing their R&D and investment burden. The green innovation effect of digital technology in heavily polluting industries is challenging to achieve. The government can encourage the adoption of digital technology for environmental protection and energy efficiency improvement through funding support for green innovation projects, tax relief or deductions, rewards for environmental protection technologies, and other incentive measures; additionally, by establishing an effective monitoring and enforcement system, imposing strict penalties on violations, and encouraging enterprises to strengthen environmental management voluntarily. Furthermore, for enterprises located in regions with moderate to low levels of economic development, the government can establish digital technology training programs, encourage cooperation between universities and research institutions to cultivate professional talents, and establish digital innovation resource centers in the region to provide resources and information on digital technology and green innovation. Simultaneously, it should specify support for the application direction and focus of digital technology in green innovation in regions with moderate to low levels of economic development, forming a direction for the development of green industries and effectively improving the green innovation level of enterprises.

Although this paper has reached reliable conclusions on the impact of digital technology on enterprises' green innovation, there are still some limitations and future research directions. First, the research sample in this paper is limited to listed companies in Shanghai and Shenzhen, China, and may not fully represent the green innovation of all enterprises. Future research can consider expanding the sample range, such as including non-listed companies, small and medium-sized enterprises, etc., to obtain more universal conclusions. Second, the digital technology index constructed in this paper is mainly based on text mining from corporate annual reports, which may not fully reflect the level of enterprises' digital technology. Future research can consider combining other indicators, such as the degree of enterprise digital transformation, digital technology application cases, etc., to build a more comprehensive digital technology index system. Third, this paper mainly discusses the mechanism of financing constraints and information constraints on the impact of digital technology on enterprises' green innovation, but there may be other potential mechanisms, such as technological spillover effects, talent flow effects, etc. Future research can consider further exploring other mechanisms to more comprehensively explain the internal logic of how digital technology affects enterprises' green innovation. Finally, this paper mainly uses static panel data models for analysis, which cannot capture the dynamic process of how digital technology affects enterprises' green innovation. Future research can consider using dynamic panel data models or time series analysis methods to more deeply study the long-term effects and dynamic evolution of digital technology's impact on enterprises' green innovation.

## Author contributions

Conceptualization, X.F. and Y.X.; methodology, X.F. and Y.X.; software, X.F.; validation, X.F.; formal analysis, X.F.; investigation, X.F.; resources, X.F. and Y.X.; data curation, X.F.; writing—original draft preparation, X.F. and Y.X.; writing—review and editing, X.F. and Y.X.; visualization, X.F.; supervision, Y.X.; project administration, Y.X.; funding acquisition, Y.X. Both authors have read and agreed to the published version of the manuscript.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

## Conflict of interest

All authors declare no conflicts of interest in this paper.

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