

Article

A Study on the Impact Mechanism of Digitalization on Corporate Green Innovation

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Abstract: With the wide application of digital technologies such as big data, cloud computing and 5G technology, the digital transformation of enterprises provides new ways for enterprises to enhance green innovation and achieve sustainable development. Starting from the resource-based view and combining signaling theory and stakeholder theory, this article empirically analyzes the impact of enterprise digitalization level on green innovation by examining the effect of enterprise digitalization level on green innovation and the inner transmission mechanism. The results show that (1) the digitalization level of enterprises can promote the improvement of green innovation, and this is not affected by the nature of property rights and the region of enterprises; (2) there is a partial mediating effect of government subsidies in the relationship between the digitalization level of enterprises and green innovation, and enterprises can obtain more innovation resources and thus promote green innovation through the improvement of digitalization level, and this effect is stronger in enterprises in eastern regions than in other regions; (3) The relationship between digitalization level and green innovation is positively affected by the fulfillment of corporate social responsibility, and the promotion effect of digitalization level on green innovation is strengthened as the degree of fulfillment of corporate social responsibility increases. This article reveals the ways in which digitalization level influences enterprise green innovation, which further enriches the theoretical study of enterprise green innovation. The article provides policy suggestions for the government to improve the level of corporate green innovation and achieve the dual carbon goal; it also provides references for enterprises to build a multi-level influence mechanism to promote the improvement of the green innovation level based on the stakeholder theory.

Keywords: digitalization; green innovation; government subsidies; corporate social responsibility



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1. Introduction

Green innovation is an important support for China to transform its economic growth mode and achieve sustainable development. In 2020, China put forward clear dual carbon targets of “peak carbon” and “carbon neutral”, and to ensure the successful completion of the dual carbon targets, in 2021, the State Council issued the “Opinions on the Complete and Accurate Implementation of the New Development Concept for Carbon Neutrality” and the “Action Plan for Carbon Neutrality by 2030” in 2021. Green low-carbon science and technology innovation is the key to achieving the dual carbon goal, and enterprises as the main innovation body [1–3] are both key producers and users of green innovation results, and play a major role in bridging the gap between technology, market and environment [4]. Therefore, it is crucial to study the factors influencing the improvement of enterprises’ green innovation level to achieve the dual carbon goal.

The digital economy is sweeping the world, and the widespread use of digital technologies such as big data, cloud computing, and 5G technology is changing the way

innovation factors are disseminated and combined, overturning the traditional enterprise innovation model, and deriving a new open innovation model based on digitalization [5]. The digitalization of enterprises relies on digital technology applications to connect enterprises, industries and industries into a whole, break through geographical restrictions, and broaden the breadth and depth of knowledge spillover from multiple innovation subjects [6]. It can provide more green innovation resources for enterprises and enhance their green innovation level. As digitalization is a major trend, how enterprises can take this opportunity to quickly become integrated into the new digital environment and drive their green transformation is directly related to their own survival and development [7,8].

Digitalization is the specific application of digital technology by companies, which enables them to access various innovation resources more quickly and conveniently. On the one hand, digitalization can improve the degree of cooperation between companies and relevant stakeholders (suppliers, partners, customers, etc.) in order to increase the market and environmental resilience of corporate innovation [9]; on the other hand, digitalization increases the knowledge interaction between firms and universities and research institutions [10], improves the success rate of corporate innovation, and reduces R & D costs. Digitalization is becoming the leading force driving innovation and green transformation, and the advantages of digitalization, such as high intelligence, provide favorable factor supply and environmental support for green innovation.

With the accelerated pace of digitalization in China, there is an urgent need to explore the mechanism of the impact of digitalization on corporate green innovation in order to fully appreciate the role of digital transformation in supporting corporate green innovation. At present, the research on the mechanism of the effect of digitalization on corporate green innovation is mostly focused on green finance [11,12] and R & D investment [13,14]. In terms of government subsidies as an important source of innovation funding channel, it plays an important role in promoting enterprise green innovation [15]. There are fewer studies on whether the digitalization of enterprises is beneficial for enterprises to obtain more government subsidies and whether it is beneficial for enterprises to use more government subsidies for green innovation.

In addition, corporate social responsibility (CSR) refers to the fact that enterprises not only create profits and assume corresponding responsibilities to shareholders and employees, but also bear responsibilities to consumers, communities, and the environment. CSR emphasizes the contribution of enterprises to the environment and society. The implementation of long-term development strategies increases the number and heterogeneity of stakeholders [16]. Different stakeholders represent different needs and interests. Stakeholders have the information and guidance effects of external value demands on enterprises [17,18], which requires enterprises to reduce costs and improve resource utilization efficiency as much as possible. Research on corporate social responsibility has proved that corporate social responsibility performance has a positive impact on green innovation [19]. Corporate social responsibility performance can not only promote green product and green process innovation, but also alleviate the dual externalities in the process of green innovation [20]. Further exploring the specific impact and internal mechanism of corporate social responsibility on corporate green innovation is of great significance in enriching the driving effect of corporate green innovation.

In view of this, this paper focuses on answering the following questions: (1) Whether the level of digitalization has a significant positive influence role on corporate green innovation. (2) By what mechanism is this effect realized? (3) Is this effect heterogeneous in terms of the nature of property rights and regional economies? (4) Does corporate social responsibility moderate the effect of digitalization on corporate green innovation?

In order to solve the above problems, this paper adopts the data of Shanghai and Shenzhen A-share listed companies from 2011–2020 as the sample, establishes a panel data model to empirically study the influence relationship between digitalization level and enterprise green innovation, and tests the transmission mechanism of digitalization level on green innovation. This not only explores the transmission mechanism of enterprise

digitalization level promoting enterprise green innovation and enriches the theoretical study of green innovation, but also provides a favorable reference for the government to formulate corresponding financial subsidy policies to solve the difficulties of enterprise digitalization transformation and green transformation, which is important for enterprises to improve their green innovation capability and achieve high-quality development.

The contributions of this article are as follows. Firstly, based on the data of listed companies, the impact mechanism of enterprise digitization on enterprise green innovation is discussed. According to the research by Li et al. [21], the mediating variable of government subsidies is added. Research has found that enterprise digitalization can not only directly promote green innovation, but also promote green innovation through government subsidies. This study enriches the theoretical research on green innovation. Secondly, this article explores the regulatory role of corporate social responsibility as the impact of digitalization on corporate green innovation, further verify the important role of corporate social responsibility in corporate green innovation. Thirdly, through heterogeneity testing, it is verified that digitalization can positively promote green innovation for enterprises with different attributes, while there are significant differences in the impact of digitalization on green innovation in regions with different levels of economic development.

2. Literature Review

2.1. Digitalization Research

Digitization is the process of changing from analog to digital form. Digitalization is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities. Digitization is the foundation of digitalization, so only by laying a solid foundation for digitization can we ensure that digitalization can scale to a higher level. Most Chinese enterprises, mainly small and medium-sized enterprises, are still in the initial stage of digitalization.

Driven by the new round of technological revolution and industrial change, digitalization is regarded as an important opportunity for enterprises to build key competencies and gain global competitive advantages. Existing studies on the impact of digitalization on economic activities have been conducted mainly from the perspectives of energy consumption, economic growth and international trade. For example, Gao and Li et al. [22] demonstrated the positive effect of digital technology development on green total factor energy efficiency using panel data from 213 prefecture-level cities in China, and the positive effect of digitalization on green total factor energy efficiency was more pronounced in cities with high levels of economic development. Borowski [23] showed that digitalization improves energy efficiency while reducing industrial energy consumption, which has a positive impact on environmental protection and sustainable development. Myovella and Karacuka et al. [24] analyzed the contribution of digitalization to economic growth and found that digitalization contributes positively to economic growth in both developed and underdeveloped countries, but among them Internet technologies contribute least to underdeveloped countries, while mobile communication technologies contribute most to economic growth in underdeveloped countries. Boikova and Zeverte-Rivza et al. [25] showed that digitalization has become a key factor of competitiveness and is an important guarantee for economic growth in Europe. In addition, Zhang [26] showed that digitalization changes the old international trade structure by influencing trade participants and trade services, thus facilitating the development of services trade.

In addition, some scholars have started to focus on the impact of digitalization on business behavior. For example, Shen and Sun et al. [27] showed that the changing structure of manufacturing forced firms to fully recognize the importance of digital and service transformation in production and R & D. Jing and Feng et al. [28] further integrate lean thinking into enterprise production management with the help of digital technology, to form a lean digital management approach and propose paths for implementing lean digitalization in traditional manufacturing enterprises with different competitive positions.

2.2. Green Innovation Research

Green innovation is the optimal decision of innovation subjects under the dual constraints of resources and ecology [29]. Existing studies have explored the drivers of green innovation at both micro and macro levels. Studies at the macro level have mainly analyzed the effect of green finance [30,31], foreign direct investment [32], knowledge diversity [33], etc., on green innovation. Yang et al. [34] investigated how green finance and environmental regulations affect green innovation in China and showed that both promote green innovation and are stronger for the eastern region than for other regions. Luo et al. [35] also studied the effects of inward direct investment (IFDI) and outward direct investment (OFDI) on green innovation in China, and the results showed that IFDI plays a positive role in developing green innovation in China, while OFDI has a reverse green technology effect on green innovation in China, and investing in foreign technology-intensive industries can obtain more green technology spillover and improve China's green innovation capacity. Liao et al. [36] analyzed the factors influencing green innovation efficiency in 284 cities in China, and found that knowledge sharing has a positive effect on urban green innovation efficiency and forms an obvious demonstration effect on the surrounding areas.

At the micro level of research, a growing body of literature suggests that green innovation can help firms gain competitive advantage [37–39], and that green innovation is conducive to improving corporate productivity, enhancing corporate reputation and image, and promoting high-quality and sustainable development. How to promote the level of green innovation in enterprises has received increasing attention from scholars.

From the internal factors of the enterprise, the enterprise green strategy [40], firm absorptive capacity [41], internal control capacity [42,43], etc., are key factors that affect the level of green innovation of firms. As Du et al. [44] divided green innovation into green product innovation and green process innovation and studied the effects of green market orientation and firm absorptive capacity on green innovation, the results showed that the impact of firm absorptive capacity on both green product innovation and green process innovation was positive, the role of green market orientation on green product innovation was significant, and the role of green process innovation was not significant. Ma et al. [45] explored the impact of internal control on green innovation and the results showed that the improvement of internal control motivates firms to increase their investment in environmental protection, which further influences green innovation.

From the perspective of external factors of enterprises, the first thing that affects the green innovation of enterprises is environmental regulation [46] and green financial policies [47]. The society attaches great importance to the environment, and strict environmental regulations increase the cost of enterprises and force them to green innovation. Green innovation is accompanied by high investment and risk for enterprises, which requires large amounts of capital, and green financial policies such as green bonds increase the proportion of long-term debt and optimize the debt structure of enterprises [48], which provides an effective way to solve the problem of difficult corporate financing. Secondly, external factors that affect the green innovation of enterprises also include relevant stakeholders in the supply chain, and the implementation of green innovation requires not only the integration of internal resources of enterprises, but also the integration of resources with customers, suppliers and other partners in the supply chain [49,50]. Finally, open innovation has become the main mode for companies to carry out innovation activities [51]. To strengthen effective cooperation among firms and address the phenomenon of free-riding [52] is one of the ways to promote active green innovation among enterprises.

2.3. Studies Related to the Role of Digitalization on Green Innovation in Enterprises

Regarding the impact of digitalization level on business innovation, a number of studies have found that digitalization makes a positive contribution to business innovation. From a macro perspective, regional digitization, especially the increase in the level of regional digital access, has a positive impact on the improvement of innovation performance [53]; from the micro-enterprise perspective, the level of enterprise digitalization

also has a positive contribution to enterprise innovation performance, setting up digital resource information sharing platforms [54] and strengthening the dynamic capabilities of enterprises [55]. It is an effective way for enterprises to improve their digitalization level and thus promote their innovation performance.

From the existing studies, the mechanism of the effect of enterprise digitalization level on the green innovation performance of enterprises is mainly manifested in the following aspects: (1) the improvement of digitalization level accelerates the speed of information sharing and dissemination, and the innovative talents can obtain richer external knowledge, which stimulates R & D personnel to devote more time to green innovation [56]. (2) The improved level of digitalization makes it easier for enterprises to obtain external knowledge, information, technology and other innovation resources, and improves the level of green technology innovation by enhancing the level of information sharing and the ability of knowledge integration [57]. (3) By building an enterprise digitalization capability system with digital connectivity, data integration, and intelligent decision making as the core, enterprises are driven to improve their innovation performance and promote their sustainable high-quality development [58]; (4) Regional digitalization level positively affects enterprise green innovation in five aspects: digital foundation, input, literacy, economy, and application [59]; accelerating regional digitalization is beneficial to the improvement of enterprise green innovation level.

In summary, although digitalization and green innovation have received increasing academic attention in recent years, there are still the following shortcomings in the relevant studies: (1) Scholars have studied the impact of individual enterprise digitalization level and regional digitalization level on enterprise innovation performance from macro and micro perspectives, and there are fewer studies on the impact of digitalization on enterprise green innovation. (2) Most studies on the impact of digitalization on corporate green innovation focus on the macro environment and digital finance, and scholars have demonstrated the impact of macro policies, regional digitalization levels and digital finance [60,61] on green innovation, while fewer studies have studied the impact of corporate digitalization on green innovation from the micro perspective. (3) Most of the studies on the influence of micro enterprises' digitalization level on green innovation focus on the influence mechanism of internal characteristics and policy environment on enterprises' green innovation behaviors, but not on the influence mechanism of government subsidies on enterprises' green innovation, however, government subsidies provide financial support for enterprises' innovation activities, and as an effective supplement to enterprises' R & D investment, they are indispensable to promoting enterprises' green innovation activities and enhancing their green innovation level at this stage. However, government subsidies provide financial support for enterprises' innovation activities, and as an effective supplement to enterprises' R & D investment, they are indispensable factors to promoting enterprises' green innovation activities and enhancing their green innovation level at this stage.

Therefore, this paper focuses on digitalization and green innovation, and examines whether the level of enterprise digitalization can enhance the level of enterprise green innovation through the path of government subsidies, and also examines the moderating effect of the level of corporate social responsibility fulfillment on the relationship between enterprise digitalization and green innovation. This study not only explores the transmission mechanism of enterprise digitalization level to promote enterprise green innovation and enriches the theoretical study of green innovation, but also provides a favorable reference for the government to formulate corresponding financial subsidy policies to solve the difficulties of enterprise digitalization and green transformation.

3. Theoretical Analysis and Research Hypothesis

3.1. Digitalization and Green Innovation

Enterprise green innovation is an innovative activity of enterprises to improve the resource utilization rate, reduce the ecological and environmental burden and achieve sustainable development [62,63]. Enterprises can seize market shares through green product innovation, realize energy saving and emission reduction through green technology

innovation, improve resource utilization efficiency through green process innovation [64], and achieve both economic and environmental goals. Meanwhile, in the era of big data, the digitalization of enterprises has become a necessary path for their survival and development, and the application of digital technologies such as artificial intelligence, Internet of Things and blockchain has changed people's production and lifestyle, which also has an important impact on the flow and allocation methods and efficiency of internal and external innovation factors of enterprises [65,66].

First, the improvement of enterprise digitalization is conducive to promoting the integration of enterprise green innovation resources. Due to the existence of information asymmetry, enterprises are more inclined to choose conventional projects with lower risk [67]. This phenomenon profoundly affects the technological innovation behavior of enterprises. The digitalization of enterprises, on the other hand, facilitates enterprises to filter out the true and effective information from the massive information, thus realizing the transparency of enterprise activities and improving the level of green innovation. First, the digitalization of enterprises makes the enterprise innovation knowledge resources gradually realize digitization, and technologies such as big data, cloud computing and blockchain provide new ways for the exchange and dissemination of innovation knowledge, and knowledge dissemination is rapidly interconnected among innovation subjects through the form of data transmission [68]. Secondly, enterprises access the innovation network through digital technology, increase the scale of innovation network, strengthen the weak relationship between innovation subjects, and enterprises can achieve diversified knowledge integration and promote green innovation by absorbing more heterogeneous knowledge [69].

Secondly, the improvement of enterprise digitalization level is conducive to reducing the cost of green innovation of enterprises. Firstly, the higher the degree of digital transformation of enterprises, the more timely the application of digital technology makes the information transmission and processing, and the cost of enterprises to obtain and screen effective R & D information is lower [70]. Second, enterprise digitalization can rapidly enhance the quality of innovative talents through learning effect and replacement effect [71] to match the quality of innovative talents with innovative technologies, reduce the cost of knowledge accumulation of innovative talents, improve the efficiency of innovation, and enhance the R & D capability of enterprises. Third, the digitalization of enterprises enables the rapid transmission and sharing of information in the supply chain, improves the ability of enterprises to respond to market demand, and reduces the cost of trial and error in enterprise R & D [27].

Based on the above analysis, the following hypotheses are formulated.

Hypothesis 1 (H1). *The level of enterprise digitalization can promote the level of enterprise green innovation.*

3.2. The Intermediary Role of Government Subsidies

Green innovation has the typical characteristics of high investment, long cycle and high risk, and it is difficult to realize economic benefits quickly through enterprises' own investment alone, thus hindering the enthusiasm of enterprises to invest in green innovation. For this reason, the government has the responsibility to guide and encourage enterprises to shift to a clean and green development model, and government subsidies, as the main means of financial subsidies, are beneficial to enterprises to carry out green innovation [72].

First, based on the basic resource view, enterprise innovation activities are inseparable from resource input, and government subsidies can compensate for the shortage of funds and take into account the short-term economic benefits of enterprises. Green innovation has the dual externalities of knowledge spillover and negative externalities of environmental resources, which increase the risks and environmental governance costs borne by enterprises [73]. In addition, the government subsidies received by enterprises increase their capital to invest in innovation activities and improve their motivation to

invest in R & D activities, which is eventually realized as an increase in the number of enterprise patent applications [74]. Wu and Liu et al. [75] demonstrated that government subsidies effectively improved firms' green innovation performance by increasing R & D investment using data from 2011 to 2016 for Chinese high-tech firms in Shanghai and Shenzhen. Ma and Zhang et al. [76] found that government subsidies help to reduce the cost of green innovation of firms, thus promoting green innovation.

Second, based on signaling theory, government subsidies represent the government's recognition of the firm, and firms labeled as recognized gain higher visibility and goodwill, and are more likely to embed in innovation networks and attract external innovation resources to supplement their own shortage of innovation resources. Huang et al. [77] found that the "signal endorsement" of government subsidies, which sends positive signals to external investors, is considered to be more conducive to creating a favorable market environment for innovation. Wang and Liu [78] found that positive signals from government subsidies can weaken information asymmetry between firms and external investors, enhance the confidence of external investors, reduce the financing cost of firms, and allocate a firm's attention resources to innovation activities, thus improving firm's innovation performance.

Based on the above analysis, the following hypotheses are formulated.

Hypothesis 2 (H2). *Government subsidies play a mediating role in the relationship between the level of digitalization and green innovation in firms.*

3.3. The Moderating Role of Corporate Social Responsibility

Enterprise green innovation activities are a process of comprehensive investment of internal and external resources, which reflects the responsibility of enterprises to improve product environmental governance standards and consumer health and safety. Actively fulfilling corporate social responsibilities can help companies obtain various tangible and intangible resources from within and outside the companies, thereby helping them better conduct green innovation activities. Carroll (1979) [79] first proposed the concept of corporate social responsibility, and believes that corporate social responsibility has a good promoting effect on corporate development. Porter [80] believes that integrating social responsibility into corporate innovation can avoid companies being punished for environmental pollution, and can also enhance their external image. More and more scholars are paying attention to the relationship between corporate social responsibility and green innovation [81,82].

Green innovation activities require a lot of time and capital investment, and there is uncertainty in the innovation process, which can lead to the loss of immediate interests of enterprises and hinder the implementation of green innovation activities. CSR is different from the traditional financial objective of "maximizing shareholders' interests" and emphasizes that corporate decisions are subject to the constraints of stakeholders, and its basic principle is based on stakeholder theory [83,84]. According to stakeholder theory, corporate stakeholders include government, consumers, the environment, and the public, etc., and companies should take responsibility for their stakeholders [85]. The governance concept of CSR requires enterprises to give more consideration to social and environmental factors, which has a high degree of fit with China's willingness to achieve carbon neutral carbon peaks and realize the dual goals of overall economic and environmental benefits. Therefore, when the degree of CSR fulfillment is higher, the higher the corporate recognition of environmental protection, and the more active the green innovation activities driven by both national policies and environmental awareness [86].

From the stakeholder perspective, when the sense of corporate social responsibility is stronger, the more stakeholder pressure the company faces, which in turn drives to invest more resources into green innovation activities and improve environmental benefits [87]. In addition, in the process of green innovation, enterprises inevitably need to obtain innovation resources from the outside, and the external technology and knowledge held by

stakeholders and the internal knowledge of enterprises are integrated with each other to provide resource support for green innovation.

Based on the above analysis, the following hypotheses were formulated.

Hypothesis 3 (H3). *CSR positively regulates the driving effect of digitalization on enterprise green innovation, i.e., the higher the degree of CSR fulfillment, the more enterprises apply the innovation resources brought by digitalization to green innovation and drive the level of enterprise green innovation to improve.*

4. Study Design

4.1. Sample Selection and Data Sources

This article selects A-share listed companies in China from 2011–2020 as the initial sample, and the initial sample is processed as follows, according to the research needs: (1) exclude the financial industry sample; (2) exclude the ST class and *ST class listed companies; (3) exclude the sample with serious missing data in the observation period. In order to avoid the influence of outliers on the empirical results, 1% and 99% quantile tailing is performed for all continuous variables.

Data sources: Green patent data from China Research Data Service Platform database; social responsibility data from Hexun.com 2011–2020 “Social Responsibility Report of Listed Companies”; digital level, government subsidies and related financial data from the CSMAR database.

4.2. Variable Selection and Measurement Methods

4.2.1. Explanatory Variable: Green Innovation

Green innovation (GI) refers to the innovation activities of enterprises that aim at low carbon and environmental protection, energy saving and emission reduction, etc., and balance economic and environmental benefits. Drawing on Feng and Wang [13], Husnaini and Bambang [88], the green patent application metric can be used to measure the green innovation level of listed companies in China. In this article, in the data processing process, we use the logarithm of green patent applications + 1 to measure the green innovation level of listed companies.

4.2.2. Core Explanatory Variable: Digitalization Level

Digitalization level (Dig) is the level of information technology application represented by digital technology application, artificial intelligence, cloud computing, big data [89]. This article draws on Verhoef et al.’s [90] approach to constructing enterprise digitization indicators using text mining keyword frequencies, with data from the CSMAR database. We used the logarithm of digitalization word frequency + 1 to measure the digitalization level of listed companies in China.

4.2.3. Intermediary Variables: Government Grants

For the measure of government subsidies, most Chinese scholars use the actual amount of government subsidies received by firms [91,92]. Drawing on Li et al. [93], the amount of government subsidies (SUB) in the financial statements of listed companies is obtained by adding 1 to take the logarithm.

4.2.4. Moderating Variable: Corporate Social Responsibility

For the measurement of corporate social responsibility (CSR), the total score in Hexun’s CSR evaluation system is used as the indicator of CSR. Based on the stakeholder theory, CSR includes five dimensions: shareholders, employees, suppliers, customers and government. Hexun’s CSR evaluation system has been evaluating the social responsibility of A-share listed companies in China since 2010, and the evaluation results contain five dimensions of CSR evaluation, and the evaluation results are authoritative and have been recognized by many scholars [94,95], therefore, the score measures CSR were selected for this study.

4.2.5. Control Variables

The factors affecting green innovation mainly come from the firm characteristics and governance level. Drawing on the relevant practices of Zou and Li [96,97], this article introduces typical variables reflecting firm characteristics and governance level as control variables. The firm characteristics variables include (1) firm age (Age), with the natural logarithm of the firm's establishment as a proxy variable; (2) firm size (Size), with the natural logarithm of the firm's total assets as a proxy variable; (3) current ratio (CR); (4) gearing ratio (LEV); (5) growth, with the sustainable growth rate of the firm as a proxy variable; (6) Tobin's Q value (TQ); (7) return on assets (ROA); (8) number of R & D personnel (RDP), with the natural logarithm of the number of R & D personnel as a proxy variable; (9) amount of R & D investment (RDI), with the natural logarithm of the amount of R & D investment as a proxy variable. Corporate governance variables include (1) equity concentration (OC); (2) board size (Board), with the natural logarithm of the number of board members plus one as a proxy variable; and (3) percentage of independent directors (IDR). The relevant variables are described and measured as shown in Table 1.

Table 1. Definition of variables and measurement methods.

Variable Type	Variables Symbols	Variable Name	Measurement Method
Explained variable	GI	Green Innovation	Green patent applications + 1 to take the logarithm
Core explanatory variable	Dig	Digitalization level	Digitalization word frequency + 1 to take the logarithm
Mediating variable	SUB	Government Grants	The amount of government grants is taken as a logarithm
Moderating variable	CSR	Corporate Social Responsibility	Social responsibility scores are taken as logarithms
Control variables	Age	Number of years in business	The number of years of business establishment is taken as logarithm
	Size	Enterprise size	Total enterprise assets are taken as logarithm
	CR	Current Ratio	Current assets/current liabilities
	LEV	Gearing ratio	Total liabilities/total assets
	Growth	Growth	Sustainable growth rate
	TQ	Tobin's Q value	Total market capitalization/assets
	ROA	Return on Assets	Net profit/total assets
	RDP	Number of R & D staff	The number of R & D staff is taken as a logarithm
	RDI	Amount of R & D investment	The amount of R & D investment is taken as logarithm
	OC	Shareholding Concentration	The sum of the shareholdings of the top 3 outstanding shareholders of the Company
	Board	Board Size	Number of board members + 1 to take the logarithm
	IDR	Percentage of independent directors	Number of independent directors/number of board of directors
	YEAR _t	Time fixed effect	Year
	PRVN _j	Province	Fixed regional effect
	IND _i	Industry	Fixed industry effect

4.3. Model

In order to verify the effect of the digitalization level of enterprises on the green innovation of enterprises, we reference to the test method of Wang et al. (2022) [98], and a common panel data model (1) is constructed to test the effect of green innovation.

$$GI_{i,t} = \alpha + \beta Dig_{i,t} + \sum \theta_i Controls_{i,t} + YEAR_t + PRVN_j + IND_i \quad (1)$$

where the subscript i denotes the firm and t denotes the year. $GI_{i,t}$ is the explanatory variable, indicating the level of green innovation of firm i in year t . $Dig_{i,t}$ is the core explanatory variable, denoting the level of digitalization of firm i in year t . $Controls_{i,t}$ denotes all the control variables of firm i in year t . $YEAR_t$ are the time fixed effects, $PRVN_j$ are regional fixed effects, and IND_i are industry fixed effects. $YEAR_t$ refers to the time when enterprise data occurs in year t as 2011, 2013, etc.; $PRVN_j$ refers to the province where the enterprise is registered, such as Zhejiang Province, Jiangsu Province, etc.; IND_i refers to the industry to which the enterprise belongs, such as specialized equipment manufacturing, high-end equipment manufacturing, etc. The control variables data are all from the CSMAR database.

5. Empirical Results and Analysis

5.1. Descriptive Statistics

This article uses stata17 for model validation. The descriptive statistics of the variables are shown in Table 2: the mean value of green innovation water of listed companies is 0.442, the standard deviation is 0.85, the minimum value is 0, and the maximum value is 3.829, which indicates that the green innovation level of enterprises is low and the gap of green innovation level among enterprises is large. The mean value of digitalization of enterprises is 1.634, the standard deviation is 1.434, the minimum value is 0, and the maximum value is 5.024, which indicates that the digitalization level of listed companies varies widely.

Table 2. Statistical description of variables.

Variables	Average Value	Standard Deviation	Minimum Value	Maximum Value	Observed Values
GI	0.565	0.937	0	3.829	14,645
Dig	1.634	1.434	0	5.024	14,645
SUB	16.08	1.886	9.839	20.29	14,645
CSR	2.961	0.631	−0.0300	4.306	14,645
Size	22.20	1.252	19.30	26.16	14,645
CR	2.633	2.527	0.320	17.20	14,645
LEV	0.392	0.191	0.0510	0.901	14,645
Growth	0.0550	0.0850	−0.535	0.383	14,645
OC	48.80	14.85	16.89	85.71	14,645
TQ	2.133	1.346	0.855	8.865	14,645
ROA	0.0610	0.0570	−0.267	0.242	14,645
Age	3.085	0.243	2.398	3.611	14,645
Board	2.108	0.195	1.609	2.708	14,645
IDR	0.378	0.0540	0.333	0.571	14,645
RDP	5.507	1.228	2.303	8.796	14,645
RDI	17.99	1.428	13.53	21.79	14,645

5.2. Benchmark Regression Results

Columns (1) and (2) of Table 3 report the results of the benchmark regression of digitalization level on green innovation. Column (1) does not include control variables, only controlling for year, region and industry fixed effects, and the results show that digitalization level has a significant impact on green innovation; column (2) adds control variables on top of column (1), and the results show that the impact of digitalization level on corporate green innovation is still significant, indicating that digitalization level has a positive incentive effect on corporate green innovation, and H1 is verified.

Table 3. Regression results of the benchmark of digitalization level and corporate green innovation.

	(1) GI	(2) GI
Dig	0.097 *** (8.073)	0.042 *** (3.779)
Size		0.065 *** (3.371)
CR		0.010 ** (2.155)
LEV		0.290 *** (3.013)
Growth		0.226 (1.155)
OC		0.001 (0.723)
TQ		−0.005 (−0.694)
ROA		0.051 (0.163)
Age		−0.156 *** (−2.717)
Board		0.163 * (1.775)
IDR		0.368 (1.248)
RDP		0.061 *** (3.248)
RDI		0.111 *** (7.152)
N	14,645	14,645
r ²	0.154	0.240
r ² _a	0.148	0.234
IND	YES	YES
YEAR	YES	YES
PRVN	YES	YES

Note: Values in parentheses represent *t*-statistics, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5.3. Endogenous Processing

To deal with the potential endogeneity, the instrumental variable method was chosen to test for it. In this article, we refer to Yang [99] and Xiao [100]’s work, the observed values of the independent variables in the prior and lagging periods are used as the instrumental variables of the current period’s independent variables, and there is a lag in the impact of digitalization level on enterprise green innovation, which means that the digitalization level of enterprises in the current period does not immediately affect the level of enterprise green innovation, therefore the digitalization level of enterprises in the lagging period and two periods as the instrumental variables to solve the endogeneity problem were used for this article. The regression results are shown in Table 4, Model 5. The instrumental variables were tested for under-identification and weak instrumental variables. The results of Kleibergen–Paap rk LM statistic show that the value of LM statistic is 2571.034 with *p*-value less than 0.01, and there is no problem of unidentifiable instrumental variables. The value of Kleibergen–Paap rk Wald F statistic is 18,000, which is greater than all critical values. There are no weak instrumental variables. The Sargan–Basman statistic corresponds to a *p*-value greater than 0.05, verifying that both instrumental variables selected are valid.

Table 4. Endogeneity and robustness test results.

	Model 1 GI	Model 2 GI	Model 3 GI	Model 4 GI	Model 5 GI
Dig	0.046 *** (3.583)	0.051 *** (3.659)	0.098 *** (3.829)	0.065 *** (5.740)	0.038 *** (4.15)
Pseudo R2			0.1174	0.1344	
Log likelihood			−14,551.419	−12,968.755	
Kleibergen–Paap rk LM					2571.034 [0.000]
Kleibergen–Paap rk Wald F					1.8 × 10 ⁴ {19.93}
Hansen J					0.282 [0.5954]
Sargan					0.276 [0.5995]
Control variables	YES	YES	YES	YES	YES
IND	YES	YES	YES	YES	YES
YEAR	YES	YES	YES	YES	YES
PRVN	YES	YES	YES	YES	YES
N	10,126	7355	14,645	14,645	6591
r2	0.248	0.244			0.3884
r2_a	0.239	0.232			

Note: (1) *** $p < 0.01$ (2) in Model 1 to Model 3, values in () represent the value of the t-statistic, in Model 4 and Model 5, values in () represent the value of the z-statistic (3) values in [] are p -values, (4) values in { } indicate the critical value of the test at the 10% significance level.

5.4. Robustness Tests

To ensure the reliability of the results, this article uses two methods of replacing the explanatory variables and replacing the econometric model for robustness testing. (1) Substitution of explanatory variables. Since the results of innovation activities have a certain lag, and innovation activities already existed before the patent application of green innovation, this article lags the green innovation variables of enterprises by one period and two periods, and the test results are shown in Model 1 and Model 2 in column of Table 4. (2) Replacement of econometric models. Because green innovation belongs to a restricted dependent variable, this article uses the Tobit model to test their robustness. Considering that green patents are non-negative and counted numbers, a negative binomial model is used to test their robustness [101]. The Tobit model and negative binomial model were selected to replace the original model for regression, and the results are shown in Table 4, Model 3 and Model 4. According to the regression results, the regression results of digitalization level on enterprise green innovation are basically consistent with the benchmark regression, which indicates that the promotion effect of digitalization level on green innovation is robust.

6. Mechanism Analysis

6.1. Mediating Effect Test

Based on the resource-based view, companies with high digitalization levels are more likely to obtain innovation resources. In this article, we use the government grants obtained as an indicator of innovation resources, and the inflow of government grant funds plays an important role in supporting companies to carry out high-input and high-risk innovation activities.

This article refers to Wen et al.'s [102] test for mediating effect. A three-step recursive model was set up to test whether government subsidies play a mediating role in the level of digitalization and corporate green innovation by adding government subsidies to Equation (1) and setting Equations (2) and (3).

$$\text{Dig}_{i,t} = \alpha + \beta \text{SUB}_{i,t} + \sum \theta_i \text{Controls}_{i,t} + \text{YEAR}_t + \text{PRVN}_j + \text{IND}_i \quad (2)$$

$$GI_{i,t} = \alpha + \beta_1 Dig_{i,t} + \beta_2 SUB_{i,t} + \sum \theta_i Controls_{i,t} + YEAR_t + PRVN_j + IND_i \quad (3)$$

Table 5 reports the regression results of mediating effects. Column (1) shows the regression results of the total effect of digitalization level on corporate green innovation, which is significant with the inclusion of control variables, fixed industry, time and region effects. Column (2) reflects the effect of enterprise digitalization level on government subsidies, and the results show that enterprise digitalization level has a significant positive contribution to government subsidies. Column (3) regression results show that both enterprise digitalization level and government subsidies have a significant contribution to enterprise green innovation. From the above analysis, it can be seen that the coefficients of the explanatory variables in the three models we have established are significantly positive and all pass the 1% significance level, indicating that government subsidies have a partial mediating role in the process of digitalization level affecting green innovation, which verifies hypothesis H2. The test results indicate that the improvement of enterprise digitalization level is beneficial for enterprises to obtain more government subsidies, and enterprises can meet the requirements of these government subsidies for innovation capital, innovation talents and other multifaceted innovation resources, and also broaden the financing channels and knowledge exchange channels through signaling, thus enhancing enterprises' core innovation resources and innovation capabilities and laying the foundation for their green innovation output.

Table 5. Regression results of mediating effects of government grants.

	(1) GI	(2) SUB	(3) GI
Dig	0.042 *** (3.779)	0.041 *** (2.761)	0.041 *** (3.710)
SUB			0.019 *** (3.803)
N	14,645	14,645	14,645
r ²	0.240	0.318	0.241
r ² _a	0.234	0.312	0.235
IND	YES	YES	IND
YEAR	YES	YES	YEAR
PRVN	YES	YES	PRVN

Note: Values in parentheses represent *t*-statistics, *** *p* < 0.01.

6.2. Moderating Effect Test

To verify the effect of the interaction between the hypothesized level of digitalization and CSR fulfillment on corporate green innovation, the following regression model was set,

$$GI_{i,t} = \alpha + \beta_0 Dig_{i,t} + \beta_1 Dig_{i,t} \times CSR_{i,t} + \sum \theta_i Controls_{i,t} + YEAR_t + PRVN_j + IND_i \quad (4)$$

where $Dig_{i,t} \times CSR_{i,t}$ denotes the cross-product term of social responsibility and digitalization level, and to avoid potential multicollinearity problems, the continuous variables social responsibility and digitalization level were decentered before regression, and then the two are multiplied to generate the interaction term.

The results of the moderating effect are reported in Table 6. From the regression results, it can be seen that the digitalization level has a significant positive impact on corporate green innovation at the 1% level, and the interaction term between digitalization level and social responsibility also has a significant positive impact on corporate green innovation at the 1% level, indicating that the moderating effect of social responsibility is significant, and social responsibility can strengthen the promotion effect of digitalization level on corporate green innovation. Specifically, for enterprises with similar digitalization level, the better a company fulfills its social responsibility, the stronger the positive promoting effect of digitalization on green innovation. The possible reasons are: firstly, the higher level of

CSR fulfillment indicates that enterprises pay more attention to environmental benefits, are willing to invest more resources in green innovation, and have higher benefits of green innovation; secondly, the higher the level of CSR fulfillment, the greater the responsibility that enterprises bear for relevant stakeholders, the closer the connection between enterprises and their relevant stakeholders, and to a certain extent the interests of enterprises and their relevant stakeholders. Secondly, the higher the degree of CSR fulfillment, the greater the responsibility of enterprises to stakeholders, the stronger the connection between enterprises and their stakeholders, and to a certain extent, the convergence of the interests of enterprises and their stakeholders, which is conducive to the development of green innovation activities representing long-term performance and social benefits.

Table 6. Moderating effects of social responsibility.

	(1) GI	(2) GI
Dig	0.042 *** (3.779)	0.042 *** (3.815)
Dig * CSR		0.018 ** (1.983)
N	14,645	14,645
r ²	0.240	0.241
r ² _a	0.234	0.234
Control variables	YES	YES
IND	YES	YES
YEAR	YES	YES
PRVN	YES	YES

Note: Values in parentheses represent *t*-statistics, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

7. Expandability Analysis

7.1. The Effect of Government Subsidies on the Relationship between Firms' Digitalization Level and Green Innovation: Based on the Difference of Property Rights Nature

The nature of property rights of listed companies in China can be divided into two forms by company attribute: state-owned enterprises and non-state-owned enterprises. Since there are significant differences between state-owned enterprises and non-state-owned enterprises in terms of regulatory strength and government subsidies, the nature of property rights may lead to differences in the effects of digitalization level on corporate green innovation and the mechanisms of government subsidies between digitalization level and green innovation. Therefore, this article divides the sample enterprises into state-owned enterprises and non-state-owned enterprises to investigate the impact of digitalization level on green innovation and the mechanism of government subsidies between the two, respectively.

The regression results in Table 7 show that the degree of digitalization has a significant effect on green innovation in both state-owned and non-state-owned enterprises, and the degree of digitalization has a significant positive contribution to government subsidies in both, and there is a partial mediating effect of government subsidies between both, therefore the influence relationship between the degree of digitalization and green innovation and the mediating effect of government subsidies between enterprises with different property rights nature is not significant. There is no significant difference. It may be due to the fact that digitalization reform has become a necessary path for the survival and development of enterprises, and green production is also a general trend. Both state-owned enterprises and non-state-owned enterprises can only access manufacturing networks and innovation networks through digitalization reform, and empower enterprise functions such as design, production and sales through digital reform, and at the same time promote a series of green innovation activities and achievements such as green manufacturing and green supply chain to save energy and reduce the emissions of enterprises, promoting the coordinated development of enterprise interests and social interests.

Table 7. Regression results of mediating effects based on heterogeneity of property rights.

	State-Owned Enterprises		Non-State Owned Enterprises			
	GI	SUB	GI	GI	SUB	GI
Dig	0.055 ** (2.076)	0.072 ** (1.976)	0.053 ** (2.022)	0.039 *** (3.250)	0.034 ** (2.110)	0.038 *** (3.206)
SUB			0.020 ** (2.127)			0.018 *** (3.074)
N	3944	3944	3944	10,701	10,701	10,701
r2	0.311	0.364	0.312	0.245	0.302	0.246
r2_a	0.290	0.345	0.291	0.236	0.293	0.237
Control variables	YES	YES	YES	YES	YES	YES
IND	YES	YES	YES	YES	YES	YES
YEAR	YES	YES	YES	YES	YES	YES
PRVN	YES	YES	YES	YES	YES	YES

Note: Values in parentheses represent *t*-statistics, ** $p < 0.05$, *** $p < 0.01$.

7.2. The Effect of Government Subsidies on the Relationship between the Digitalization Level of Enterprises and Green Innovation: Based on Regional Economic Level Differences

In order to further investigate whether there are significant differences between different regions in the impact of enterprise digitalization level on green innovation, this article divides the sample enterprises into enterprises in the eastern region and enterprises in other regions, according to the provinces where the listed companies are registered, and carries out group regression tests on the two subsamples.

The regression results in Table 8 show that the coefficients of digitalization level in both eastern region and other regions are significantly positive, indicating that regardless of the region of the company, the company can promote green innovation through digitalization, which is consistent with the H1 hypothesis. The results of the group test for the mediating effect show that government subsidies play a partial mediating role between digitalization level and green innovation in the eastern region, while in other regions, government subsidies do not play a mediating role between digitalization level and green innovation. The reasons for this result may be: (1) the economic development level in the eastern region is significantly higher than other regions, most of the listed companies are registered in the eastern region, and compared with other regions, the infrastructure construction and talent gathering degree in the eastern region are relatively strong, and enterprises improve their digitalization level while more government subsidies are used for the improvement of enterprises' green innovation capability to meet their long-term development needs. Therefore, government subsidies play an obvious intermediary role in enterprises in the eastern region. (2) Enterprises in other regions, with relatively weak economic levels, have relatively limited access to innovation resources and care more about stable development, which hinders the willingness of enterprises to carry out such high-risk activities as green innovation, so government subsidies are more often invested in business operations.

Table 8. Regression results of mediating effects based on regional heterogeneity.

	Eastern Region		Other Areas			
	GI	SUB	GI	GI	SUB	GI
Dig	0.044 *** (3.343)	0.041 ** (2.371)	0.043 *** (3.272)	0.033 * (1.679)	0.034 (1.127)	0.033 * (1.676)
SUB			0.024 *** (3.904)			0.001 (0.175)
N	10,496	10,496	10,496	4149	4149	4149
r ²	0.241	0.333	0.243	0.277	0.316	0.277
r ² _a	0.234	0.327	0.236	0.258	0.298	0.258
Control variables	YES	YES	YES	YES	YES	YES
IND	YES	YES	YES	YES	IND	YES
YEAR	YES	YES	YES	YES	YEAR	YES
PRVN	YES	YES	YES	YES	PRVN	YES

Note: Values in parentheses represent *t*-statistics, * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

8. Research Conclusions and Insights

8.1. Research Findings

Through an empirical analysis of panel data of listed companies from 2011–2020, this article explores the inner mechanism of the impact of enterprise digitalization level on green innovation by combining resource-based view, stakeholder theory and signaling theory. The results of the three hypotheses in this article are shown in Table 9. The results show that (1) the level of enterprise digitization can promote the improvement of green innovation level, and this influence is not affected by the nature of enterprise property rights and the region in which the enterprise is located, i.e., the level of enterprise digitization has a significant impact on the improvement of green innovation performance regardless of whether the enterprise is state-owned or non-state-owned, or in the eastern region or other regions. (2) Government subsidies play a part in mediating the relationship between enterprise digitalization level and green innovation. With the improvement of enterprises' digitalization level, enterprises spend more government subsidies on green innovation, which in turn promotes the improvement of green innovation level, and this effect is stronger for enterprises in the eastern region than for enterprises in other regions. (3) The relationship between digitalization level and green innovation is positively affected by the fulfillment of corporate social responsibility. As enterprises fulfill their social responsibility, the promotion effect of digitalization level on green innovation is strengthened.

Table 9. Hypothesis test results.

Hypothesis	Supported/Rejected	Test Results
H1	supported	The level of enterprise digitalization can promote the level of enterprise green innovation.
H2	supported	Government subsidies play a mediating role in the relationship between the level of digitalization and green innovation in firms
H3	supported	CSR positively regulates the driving effect of digitalization on enterprise green innovation

The theoretical significance of this article is that (1) The existing literature mostly studies the impact mechanism of digitalization on enterprise green innovation from the perspective of internal factors [103] and government regulatory pressure [104]. This article studies the impact mechanism of digitalization on enterprise green innovation from the perspective of government support and stakeholders. The article expands the theoretical research on green innovation. (2) It analyzes the heterogeneity of government subsidies in terms of the effect of digitization on corporate green innovation according to the na-

ture of property rights and regional economic level. The research of Li et al. [21] shows that digitalization has a more significant role in promoting green innovation in high-tech companies. This article expands relevant research and discusses the intermediary effect of listed companies in groups based on the nature of property rights and regional economic level. (3) It explores the strengthening effect of corporate social responsibility on digitalization for corporate green innovation by using corporate social responsibility as a moderating variable.

The practical significance of this article is: (1) This article finds the role of digitalization on enterprise green innovation through government subsidies, and provides an empirical basis for the government to formulate relevant policies to promote enterprise green innovation according to the differences in regional economic levels and differences in enterprise property rights. (2) This article analyzes the moderating role of the degree of corporate social responsibility in digitalization and corporate green innovation, and provides a reference basis for the government to formulate a constraint mechanism for corporate social responsibility and for enterprises to build a multi-level influence mechanism to promote green innovation. (3) To provide help for achieving the double carbon goal of sustainable development.

8.2. Management Insights

(1) Accelerate the digital transformation of enterprises to enhance green innovation performance. The improvement of enterprise digitalization level can promote the improvement of enterprise green innovation level, therefore enterprises can make use of the opportunity of digitalization, strengthen the absorption and utilization of external innovation resources, promote the deep integration of digital technology represented by big data and cloud computing with green innovation elements, and then break through the green technology bottleneck and realize the unification of economic benefits and social and environmental benefits of enterprises.

(2) Increase government subsidies to build a green innovation system. This article finds that government subsidies can provide new sources of funds for enterprises' green innovation, therefore, strengthening the investment of special funds for digitalization reform and green innovation can stimulate enterprises' motivation to enhance green innovation through digitalization reform. In addition, enterprises should make full use of the resource channels and information media of digital technology in the process of green innovation, absorb innovation funds from multiple sources, and effectively play the incentive role of digitalization for green innovation.

(3) Increase the publicity and restraint of corporate social responsibility to promote the green transformation of enterprises. The degree of fulfillment of corporate social responsibility can regulate the promotion of green innovation by digitalization level, therefore, in the process of promoting the green transformation and high-quality development of enterprises, in addition to improving the carbon trading mechanism, laws and regulations constraint mechanism and other systems, we should also strengthen the publicity of corporate fulfillment of social responsibility, strengthen the communication and cooperation between enterprises and stakeholders' interests, enhance the social and environmental awareness of enterprises. More resources should be invested in green innovation to achieve a win-win situation for society.

9. Limitations and Future Studies

Although the research models introduced have universal significance, this study still has some limitations. First, the data used in this study were limited to the Chinese context, and the generalizability of the research results may be questioned. Secondly, this study does not consider the possibility of other innovation funds being used for green innovation in a digitalization environment. Therefore, future research should expand the scope of research as much as possible. On the one hand, we should collect data from more countries;

on the other hand, we should explore more funding sources for enterprises to use for green innovation.

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