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Digital Economy, R&D Investment, and Regional Green Innovation—Analysis Based on Provincial Panel Data in China

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Abstract: The digital economy plays an important role in promoting regional green innovation. Based on the panel data of 30 provincial administrative regions in mainland China (except Tibet) from 2011 to 2018, this paper constructs a comprehensive development index of the digital economy and explores the potential path of the digital economy affecting regional green innovation through factor analysis and regression analysis. The results show the following: Firstly, the digital economy can effectively promote regional green innovation capability. The causal relationship is mainly realized through scientific research funds and human resources. Secondly, in terms of regional heterogeneity, the role of the digital economy in promoting green innovation and R&D investment in eastern China is stronger than that in central and western China. Thirdly, further analysis showed that the digital economy has a significant nonlinear influence on regional green innovation capability. This feature is mainly reflected in the influence of R&D personnel on regional green innovation. Therefore, the rational allocation of R&D resources is conducive to the development of regional green innovation. Finally, it is suggested to improve the two mechanisms of R&D funds and personnel investment to actuate regional green innovation development.

Keywords: digital economy; R&D funds; R&D personnel; green innovation

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1. Introduction

The rapid growth of China's economy has caused serious environmental pollution and restricted the high-quality development of the economy [1], so the coordination between economic growth and ecological protection has gradually attracted attention [2]. The infiltration and integration of information technology and economy indicates that the world has entered the era of the digital economy, and the digital economy has become a new engine to drive economic transformation and industrial structure upgrading [3]. As the digital economy grows, the relationship between the digital economy and the environment is becoming more and more important for sustainable development [4]. Modern enterprises are facing many environmental challenges and pressures, while managers have gradually realized that green innovation can enhance competitive advantages [5–7]. Green innovation activities aim at reducing the impact of products and production processes on the natural environment [8] and improving environmental protection [9,10]. It includes new production processes, new products or services, and new management and business methods. Such innovation can prevent or reduce the risk of negative impacts on environmental pollution and resource use in related activities [11,12].

The government supports green innovation. The development of green innovation technology is significant and challenging and requires the common participation of the society in China. The report of the 19th National Congress of the Communist Party of China proposed to "build a market-oriented green technology innovation system". The "13th Five-Year Plan for National Economic and Social Development of PRC" shows that industrial green development has achieved remarkable results. The "14th Five-Year Plan for Industrial Green Development" points out that the industrial field focuses on the green transformation of traditional industries. Supported by green technology innovation and guaranteed by the implementation of laws and standards, green manufacturing projects have been vigorously implemented. The construction of green manufacturing systems has also become an important support for green transformation. It is of great significance to develop green innovation technology in China; however, there are still many difficulties. Firstly, in recent years, China has begun to attach importance to green development, but technological innovation is not yet mature. It faces great risks and uncertainties in the early investment and exploration stage [13]. Secondly, the strength of intellectual property rights needs to be improved. China has issued relevant laws and regulations, but the attention to and protection of green innovation technology are far from enough [14]. In addition, green innovation technology should not only realize the protection of the environment but also consider the sustainable development of the environment, local economy, employment, and other aspects [15]. Therefore, considering the digital economy environment, it is very necessary to study green innovation, which will help to improve environmental protection and promote the sustainable development of green industry and society.

At present, studies in related fields are mainly focused on the following aspects. In the digital economy, studies pay attention to intellectual property rights [14,16], spatial characteristics and driving factors [17], pollutant emissions [18], industrial transformation and high-quality development [19], user innovation [20], and enterprises innovation [21]. Most studies about corporate innovation keep a watchful eye on innovation dynamics [22], internal control [23], green innovation [5–7], and prerequisites for the development of innovation activities [24]. In terms of regional green innovation, many scholars have explored spatial heterogeneity [25], innovation performance [14], and environmental protection [26]. The relevant influencing factors include related policies [27], environmental regulation [28], and corporate social responsibility [29]. However, less attention has been paid by the academic community to the interplay between the digital economy and green innovation. The latest studies have shown that green innovation has a significant positive impact on high-quality economic development [30], which is conducive to improving the quality of economic development in local and neighboring cities [31]. In turn, the economy drives the development of green innovation [32]. Recent research argues that the digital economy improves the green innovation of cities through industrial restructuring [33], and technological innovation is a vital way for the digital economy to improve the efficiency level of the green economy [34]. At the global level, there is diversity in the level of digital economy development in different countries. The digital economy index of countries along the Belt and Road has obvious aggregation characteristics and a cascade development pattern, with regional polarization in central and eastern Europe and regional lag in South Asia [35]. For small manufacturing firms in developing countries, the relevant R&D resources can facilitate firm innovation. Small firms in Pakistan tend to favor green process innovation over green product innovation [36]. However, internal R&D activities in Chinese companies do not have an effective impact on process innovation, and internal R&D activities in Korean companies have a negative impact on process innovation [37].

Among the above literature, it is found that, although the previous literature has paid attention to the trend of green development in the digital environment, there is a lack of research on the impact of the digital economy on green innovation capability. This research makes the following contributions: First, this paper attempts to explain the impact of the digital economy on green innovation capability from a new perspective of R&D investment. Second, a relevant analysis of the digital economy and green innovation was conducted before the argument so as to fully consider the influence of the external environment. Third, this paper complements and verifies the regional heterogeneous impact of the digital economy on green innovation and R&D investment. Fourth, it examines whether there is a nonlinear relationship between the digital economy and green innovation capability and, if so, what the possible causes are.

2. Theoretical Analysis and Research Assumptions

2.1. Digital Economy and Regional Green Innovation

The formation of the digital economy is inseparable from the rapid development of ICT (Information Communication Technology) and digital finance. From the enterprise aspect, according to the technological innovation theory by Joseph Alois Schumpeter, ICT is introduced into the production system as a new production factor, which realizes the recombination of production factors and facilitates technological innovation. Manufacturing digitization has a positive impact on green process innovation [38]. Simultaneously, ICT gives full play to the advantages of resource sharing and efficient information circulation, improves enterprise management efficiency, and reduces management and technology costs [39]. In order to enhance their competitive advantage, enterprises will constantly adjust their product structure and upgrade their industrial structure, thereby improving the utilization efficiency of various element resources, reducing the waste and consumption of resources and pollution emissions in the production process, and raising the efficiency of the green economy [40]. From the regional aspect, ICT can accelerate the flow of regional innovation elements and the spillover and release of innovative knowledge, which helps inter-regional enterprises to learn green technology and boost regional green innovation [41].

Digital finance can actuate the process of digital industrialization and industrial digitization. Most scholars believe that financial development can bring green innovation [42–44]. Financial institutions provide financial services to the real economy to meet its development requirements. The green innovation activities of enterprises are facing greater risks, longer product development cycles, and higher uncertainty, which make it difficult for some enterprises to obtain bank loans. When the green innovation activities of enterprises face insufficient internal financing, they will rely on external financing to provide financial support. The supply of financial resources is the core guarantee for micro-enterprises to carry out green innovation activities, and digital finance broadens the financing channels for green innovation of small- and medium-sized enterprises [45]. The combined application of digital finance and information technology can effectively reduce the information asymmetry and establish scientific and complete risk prevention and control systems. Then, financial institutions can accurately judge customers based on their information and provide more credit for high-quality green innovation projects, thereby expediting the smooth implementation of green R&D projects invested by enterprises [46,47]. The digital economy promotes the high-quality development of manufacturing industry and industrial transformation through technology introduction and independent innovation. The secondary industry with more high-pollution industries has gradually changed to the tertiary industry, reflecting greener industrial transformations and higher innovation trends [19,33]. Moreover, innovation is not only a competitive advantage to increase profitability but also an important factor for sustainable development of the company. Based on the above analysis, the following hypothesis is proposed.

H1: *The development of the digital economy plays a positive role in promoting regional green innovation.*

2.2. Digital Economy, R&D Investment, and Regional Green Innovation

The digital economy realizes the digitization of production factors, optimizes the structure and management of enterprises, improves the efficiency of enterprise supply chains, saves costs, and increases profitability. On the one hand, advancements in the production efficiency of enterprises can release more idle resources for independent research and development, thus expediting the efficient flow of high-tech talents [48]. The process of the digital economy formed by digital technology combined with economic development and its integration function is socially recognized, forming a siphon effect of human capital and providing a guarantee for the manpower base of R&D investment. The development of the digital economy enhances social innovation participation, innovation vitality, and the innovation talent pool, which in turn increase R&D investment, and R&D activities bring technological progress [49]. China has been emphasizing increasing R&D investment, with all 30 of its provinces increasing their R&D investments between 2006 and 2017. Therefore, the following hypotheses are proposed.

H2: *The development of the digital economy helps to increase R&D funds input.*

H3: *The development of the digital economy helps to increase R&D personnel input.*

The increase in R&D investments is conducive to stimulating the enthusiasm of enterprises to carry out R&D activities, offsets risks such as failure of R&D activities to a certain extent, and increases the output of R&D activities [50]. A study showed that the R&D investment of enterprises in information technology is an important source of economic output and productivity growth. Long-term R&D investment will lead to the economic growth of enterprises, but the premise is that the direction of the enterprise's R&D investment is correct [51]. From another perspective, when the human capital level matches the R&D funds input, the R&D investment of enterprises can be positively transformed into advanced technological achievements to boost the progress of green technology [52]. Green technology helps enterprises to save resources and reduce costs reasonably, while non-clean technology is not conducive to the progress of green technology. Enterprises will make technology choices in pursuit of profit maximization [53]. Furthermore, the digital economy reduces air pollution by changing the industrial structure, and the growth of more energy-efficient sectors will cut emissions [33,54]. E-commerce spawned by the digital economy can improve environmental pollution. Compared to personnel shopping, supply and demand resources in the e-commerce model reduce transportation and distribution costs and energy consumption [55]. The digital economy realizes green development under the value chain sharing economy by reconstructing the industrial value chain. Figure 1 shows the research framework of this section. This paper thus proposes the following hypotheses.

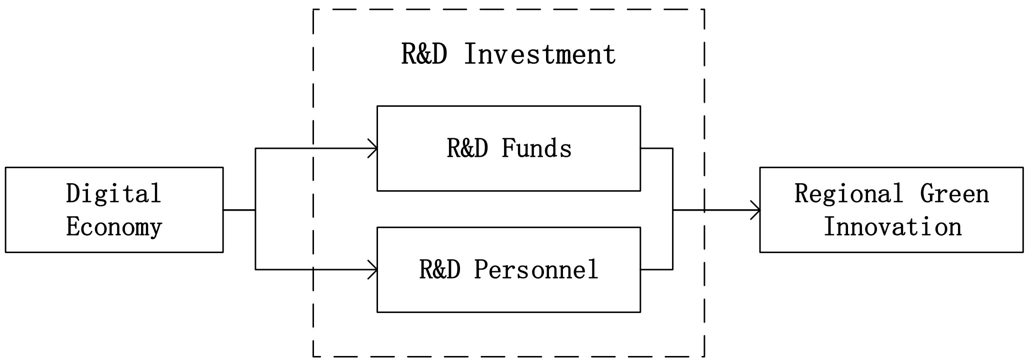

Figure 1. Research framework.

H4: *R&D funds play a certain intermediary role in the process of digital economy promoting regional green innovation.*

H5: *R&D personnel play a certain intermediary role in the process of digital economy promoting regional green innovation.*

3. Research Design

3.1. Model Settings

In order to investigate the impact of the digital economy on regional green innovation, the following model was established:

$$Gin_{it} = \alpha_0 + \alpha_1 Dig_{it} + \alpha_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{1}$$

In order to investigate the impact of the digital economy on R&D investment, the following models were established:

$$RDp_{it} = \beta_0 + \beta_1 Dig_{it} + \beta_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{2}$$

$$RDh_{it} = \gamma_0 + \gamma_1 Dig_{it} + \gamma_2 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{3}$$

In order to investigate the mediating effect of R&D investment, the following models were established:

$$Gin_{it} = \delta_0 + \delta_1 Dig_{it} + \delta_2 RDp_{it} + \delta_3 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{4}$$

$$Gin_{it} = \eta_0 + \eta_1 Dig_{it} + \eta_2 RDh_{it} + \eta_3 X_{it} + \lambda_i + \mu_t + \varepsilon_{it} \tag{5}$$

where Gin_{it} is the explained variable, representing the level of regional green innovation; Dig_{it} is the explanatory variable, referring to the development level of the digital economy; RDp_{it} represents the R&D funds input; RDh_{it} represents the R&D personnel input; X_{it} represents a series of control variables, mainly including the regional economic level, regional government support, regional external investment, and the regional technical level; α_0, β_0, γ_0, δ_0, and η_0 represent the intercept terms; λ_i represents the regional fixed effect and μ_t represents the time fixed effect; ε_{it} represents the random disturbance term; i represents the province; and t represents the year. This study controls both the time fixed effect and the province fixed effect, which can effectively address the impact of policy exogenous shocks and province-fixed characteristics on the research results.

This paper establishes mediating effect models, and the process of the mediating effect analysis is as follows. Firstly, the paper tests whether the digital economy in model (1) has a significant effect on regional green innovation: if it is not significant, it proves that the digital economy has no direct relationship with regional green innovation, and the test stops; otherwise, it shows that the digital economy significantly affects regional green innovation. On this basis, model (2) and model (3) are continued to test whether the digital economy has a significant effect on R&D investment, including R&D funds and R&D personnel: if not, it shows that the digital economy has no direct relationship with R&D investment and R&D investment does not play a mediating effect, and the test stops; if significant, it shows that the digital economy significantly affects R&D investment. Finally, we continue to test model (4) and model (5) and then observe the effects of the digital economy and R&D investment on regional green innovation at the same time: if both are significant to green innovation, there is a partial mediating effect of R&D investment; if the effect of the digital economy is not significant but the effect of R&D investment is significant, it indicates that R&D investment plays a full mediating effect.

3.2. Variable Description

3.2.1. Explanatory Variables

Digital Economy Index. Based on the existing research [56], five indicators were selected to measure the level of the digital economy, including the digital inclusive finance index, the number of internet broadband access users, the proportion of employees in the computer service and software industry to employees in urban units, total telecom business, and mobile phone penetration. For the development of digital finance, the China Digital Inclusive Finance Index was adopted, which was jointly compiled by the Institute of Digital Finance of Peking University and Ant Financial Services Group. Through the method of factor analysis, the data of the above five indicators were standardized and then processed to reduce the dimension to obtain the comprehensive development index of the digital economy.

The results show that the KMO value of these five indicators is 0.642. The chi-squared value of the LR test is 637.29, and the p-value is 0.0000. The model is very significant, indicating that the selected indicators are suitable for factor analysis. After that, two common factors were extracted, and the cumulative variance contribution rate reached

82.26%, indicating that the extracted common factors can better reflect the comprehensive development index of the digital economy. Finally, the comprehensive digital economy development index was obtained based on the contribution rate of the two common factors, and the proportions after factor rotation are 0.4291 and 0.3935. The relevant indicators are described in Table 1, and the analysis is shown in Tables 2 and 3.

$$\begin{gathered}
\kappa_1 = DF \times 0.20577 + IU \times 0.48635 - PE \times 0.19572 + TB \times 0.45109 \\
- MP \times 0.01595 \\
\kappa_2 = DF \times 0.20650 - IU \times 0.15525 + PE \times 0.53358 - TB \times 0.07035 \\
+ MP \times 0.46005 \\
Dig = (0.4291 \times \kappa_1 + 0.3935 \times \kappa_2) \div 0.8226
\end{gathered}$$

Table 1. Construction of digital economic indicators.

Digital Economy Development Level	
DF	The digital inclusive finance index
IU	The number of internet broadband access users (ten thousand)
PE	The proportion of employees in the computer service and software industry to employees in urban units (%)
TB	Total telecom business (one hundred million CNY)
MP	Mobile phone penetration (piece/one hundred people)

Table 2. Factor analysis.

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	2.72927	1.34532	0.5459	0.5459
Comp2	1.38396	0.87825	0.2768	0.8226
Comp3	0.50570	0.29220	0.1011	0.9238
Comp4	0.21350	0.04593	0.0427	0.9665
Comp5	0.16757	—	0.0335	1.0000

Table 3. Common factor extraction.

Variable	Comp1	Comp2
DF	0.20577	0.20650
IU	0.48635	−0.15525
PE	−0.19572	0.53358
TB	0.45109	−0.07035
MP	−0.01595	0.46005

3.2.2. Explained Variable

Regional green innovation capability (Gin). There is no uniform understanding of regional green innovation capability in relevant studies. Different scholars use different metrics to measure green innovation, such as the green innovation index [57]; the Malmquist-DEA index method, which measures the efficiency of green technology innovation [58]; and the number of green patents [59,60]. Considering that the number of patents can more intuitively reflect the technological innovation output capability of enterprises, and there are no specific statistics on the output value of new green products in China, this paper evaluates the number of green patent applications rather than the number of patents granted. This is because patented technology is likely to have an impact on business performance during the application process, so patent application data are more stable, reliable, and timely [61]. In addition, there are some external uncertainties in the number of green patents granted [33]. The number of green patent applications can accurately reflect the innovation capability and vitality of a region [62]. The higher the number of patent applications is, the higher the innovation capability is. Generally speaking, the rank of patents based on innovativeness is, in descending order, invention patent, utility model patent, and design patent [63]. Green invention patents will help enterprises to save energy and reduce carbon emissions [64]. Based on the information related to green patents published in the CNRDS database, this paper selects the number of green invention patent applications as a measure of green innovation capability, and the number of green utility model patent applications is used to conduct a robustness analysis on the empirical results. The number of green invention patent applications at the provincial level was calculated from the number of green invention patent applications at the prefecture level.

3.2.3. Intermediary Variables

R&D investment. The impact of the digital economy on regional green innovation may be twofold: firstly, the development of the digital economy increases the investment of enterprises in research funds; secondly, the digital economy stimulates the investment of enterprise researchers, which in turn promotes regional green innovation. The digital economy has a positive effect on R&D investment, innovation agents, innovation organization, and innovation processes in each region and can promote R&D funding [65]. Corporate R&D investment affects innovation performance and is an important foundation and prerequisite for firms to carry out innovative activities. Increases in the scale and intensity of R&D investment will lead to a greater innovation performance [66]. This paper examines R&D expenditure (RDp) and human personnel (RDh) in R&D investment, which are represented by R&D funds internal expenditure and R&D personnel discounted full-time equivalent.

3.2.4. Control Variables

(1) Regional external investment. It is measured by foreign direct investment (FDI). FDI enhances China's green technology innovation through green technology spillover. China can acquire green technology from developed countries to enhance the diffusion and capacity of green innovation [67]. Some research shows that FDI may have different impacts in different countries and regions. In China, FDI has advantages and disadvantages: it brings high economic growth through high investment and consumption and relieves the pressure of insufficient funds in the process of green innovation. However, it may bring high emissions and ample pollution [68].

(2) Regional economic development level (Pgdp). The regional economy reflects the development level of information technology and financial resources to a certain extent. From the perspective of enterprises, economic development to a certain extent can help enterprises to assume more social responsibilities, think about green reform, and then boost the local green innovation capability. In this paper, regional Pgdp is used to measure the development level of regional economics [69].

(3) Regional government support (Sout). In practice, the government always intervenes and guides innovation subjects to carry out science and technology innovation activities—mostly in the form of financial support—which, to a certain extent, makes up for the funding gap of enterprise R&D funds and reduces the risk of enterprise innovation. Some scholars have found that the patent output of enterprises is more dependent on government science and technology funding; the funded enterprises have a stronger innovation output capacity and are more likely to make patent applications [70]. The higher the degree of government funding is for science and technology, the more patents the company produces [71]. Therefore, this paper uses science and technology expenditure to measure government support.

(4) Regional technical level (Tecm). This is expressed in terms of technology market turnover. In the network economy, manufacturing enterprises rarely rely on internal R&D, instead obtaining the required external knowledge through the technology market. In the knowledge-based economy, the innovations required for the development of enterprises can be obtained through the technology market, thus making up for the lack of internal innovation [72]. The technology market is a strong driving force for innovation, especially high-quality innovation, and the more developed the regional

technology market is, the stronger the drive for high-quality innovation is. Technology market turnover has a positive effect on science and technology innovation [73].

4. The Spatiotemporal Changes of the Digital Economy and Regional Green Innovation

4.1. Change Analysis

Based on the representative variables of the above indicators, the digital economic index and the number of green invention patent applications of 30 provinces, autonomous regions, and municipalities directly under the Central Government (except Hong Kong, Macao, Taiwan, and Tibet) in China were selected to draw trend charts from 2011 to 2019. The 30 provinces are divided into three parts: eastern, western, and central. The eastern region includes Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan, a total of 11 provincial administrative regions; the central region includes Heilongjiang, Jilin, Shanxi, Anhui, Jiangxi, Henan, Hubei, and Hunan, a total of eight provincial administrative regions; and the western region includes Sichuan, Chongqing, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Guangxi, and Inner Mongolia, a total of 11 provincial administrative regions. Figure 2 shows the changes in the digital economy in China overall as well as the east, center, and west from 2011 to 2019, and Figure 3 shows the changes in the number of green invention patents. It can be observed that the digital economy shows an upward trend from 2011 to 2019, and the east, center, and west remain basically consistent. The number of green invention patents in the country also shows an upward trend from 2011 to 2018 but decreases in 2019. At the international level, the latest figures released by the World Intellectual Property Organization (WIPO) show that international patent applications in the field of green technologies (PCT) barely grew in 2019 [74]. According to the World Intellectual Property Indicators series of reports, the number of patent applications received by the State Intellectual Property Office of China in 2019 fell by 9.2% compared to 2018, the first decline in China in nearly 24 years, which the report interpreted as a result of China's increased efforts to optimize the application structure and improve the quality of applications in the overall supervision of patent applications [75]. In addition, the global COVID-19 pandemic has changed the external environment for science and technology innovation in China, reducing the opportunities for offline staff communication, increasing the cost and risk of science and technology innovation, and thus inhibiting innovation dynamics [76]. Furthermore, the number of patents for green inventions showed a significant increase after 2015 for the following possible reasons. In 2015, the State Council issued "the Guiding Opinions on Actively Promoting the "Internet+" Action". China attaches great importance to the development of the ecological environment from a strategic perspective, and the national policy will influence the green innovation momentum of each region [33]. In addition, the State Intellectual Property Office issued the "Patent Agency Industry Reform Pilot Work Plan", which relaxes the restrictions on the conditions for shareholders or partners of patent agencies, which shows the government's support for innovation.

In order to study the degree of influence of the relevant environment, the number of green patents in 2020 was added, which still has a decreasing trend compared with the previous year, and it can be seen that the external environment has a long time and a large degree of influence. Therefore, the research time span of this paper covers the period from 2011 to 2018.

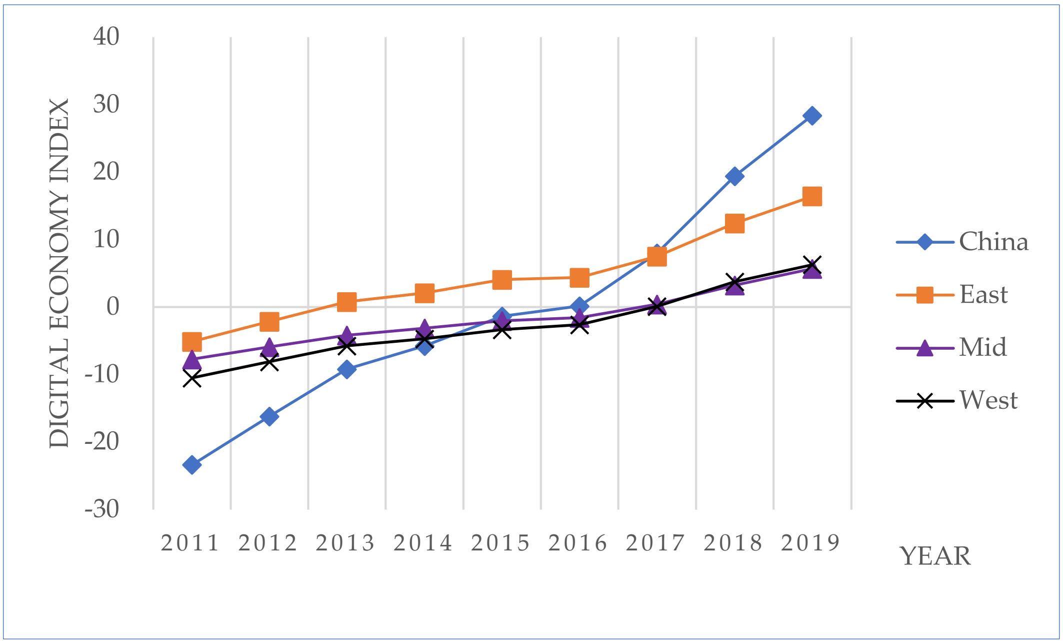

Figure 2. Digital economy trends.

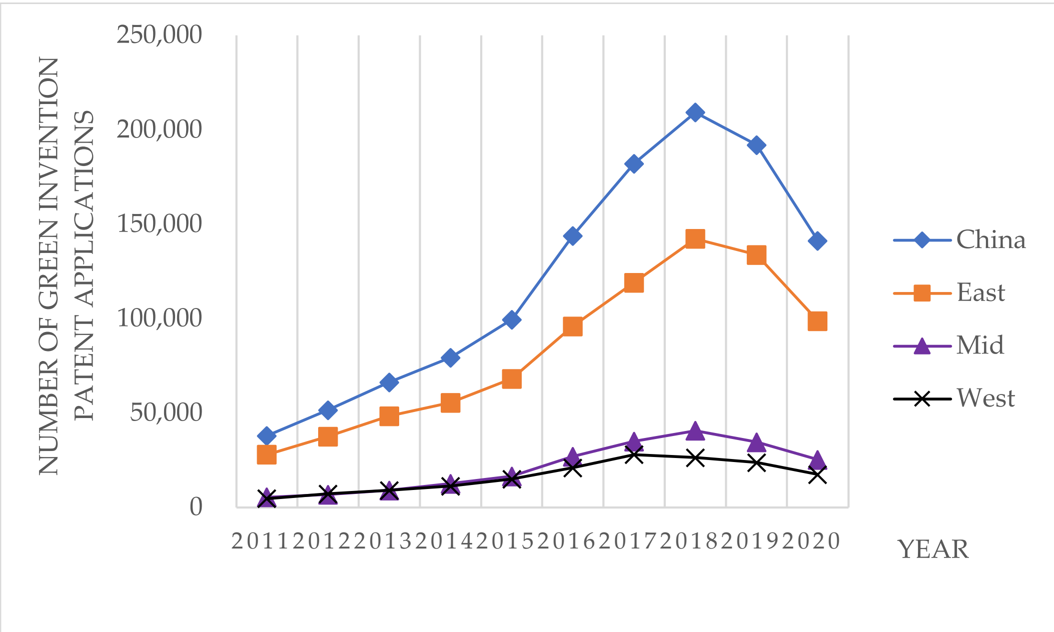

Figure 3. Green innovation trends.

4.2. Data Description

In this paper, the panel data of 30 provinces, autonomous regions, and municipalities directly under the Central Government of China (except Hong Kong, Macao, Taiwan, and Tibet) from 2011 to 2018 are used; the data were carefully verified, and individual missing data points were filled in to finally obtain a valid data sample of 240. In order to eliminate the influence of the data dimension and reduce the error, the data were standardized in the model. The main data sources of this paper include the *China Statistical Yearbook*, *China Statistical Yearbook On Science And Technology*, and the CNRDS database. The variable definitions and indicators are shown in Table 4, and the distribution of variables can be obtained based on the data in Table 5.

Table 4. Variable definition and calculation method.

Variable	Definition	Calculation	Unit
Gin	Region green innovation	The number of green patent applications	Piece
Dig	Digital economy indicators	Principal components of the digital economy (from factor analysis)	
RDp	R&D funds input	R&D funds internal expenditure	10,000 CNY
RDh	R&D personnel input	R&D personnel discounted full-time equivalent	Man-year
Pgdp	Regional economic level	Per capita GRP	CNY
Sout	Regional government support	Expenditure for science and technology	100 million CNY
FDI	Regional external investment	Total investment of foreign funded enterprises	100 million USD
Tecm	Regional technical level	Technology market turnover	10,000 CNY

Table 5. Variable descriptive statistics.

Variable	Observation	Mean	Max	Min	SD
Gin	240	0	5.4375	−0.6852	1
Dig	240	0	4.6018	−1.5632	1
RDp	240	0	4.3494	−0.7634	1
RDh	240	0	4.7709	−0.7440	1
Pgdp	240	0	3.5250	−1.4683	1
Sout	240	0	6.8555	−0.7940	1
FDI	240	0	7.0338	−0.6114	1
Tecm	240	0	7.0602	−0.4798	1

5. Empirical Results and Discussion

Before regression analysis, Hausman test was conducted to determine whether the model should adopt fixed effect or random effect. The results show that the *p*-value is 0.0000, which can basically reject the null hypothesis, so the fixed effect model was selected for regression analysis.

5.1. The Influence of the Digital Economy on Regional Green Innovation

The regression results of OLS are shown in Table 6; column (1) and column (2) respectively represent the regression results without and after the addition of control variables when the explained variable is the number of green invention patent applications. Without the addition of control variables, the digital economy can effectively promote regional green innovation at a significance level of 1%. Specifically, for every 1% change in the digital economy index, the regional green innovation index has a positive change of 1.5555%. After the addition of control variables, the relationship between the two is still valid. For every 1% change in the digital economy index, the regional green innovation index has a positive change of 0.5930%.

The above results show the causal relationship between the digital economy and regional green innovation—that is, the digital economy significantly facilitates regional green innovation development. The mechanism may be that the digital economy urges the construction of a more complete financial system and information technology. Driven by the digital economy, digital finance benefits from the introduction and integration of internet technology and traditional financial industry. Under the new digital service mode, the pressure faced by banks has soared, so they have to reform themselves and improve their ability to serve the real economy. In addition, digital finance expands the scope of financial services with an extremely low cost and service threshold, which is more conducive to reaching small- and medium-sized enterprises. For regions that attach importance to green innovation, the government and banks are bound to pay attention to and support green innovation projects of enterprises, which provides a source of funds for innovation activities. Furthermore, relying on the powerful data processing capability of internet technology, the information transmission of enterprises is faster and the channels for obtaining information are more extensive, which improves the market environment and is conducive to technological innovation of enterprises. With the continuous improvement of environmental regulation and production environmental protection standards, enterprises have to consider greener production methods and technological innovation, which means that enterprises increase their competitiveness through green technology research and development.

Table 6. Influence of the digital economy on green innovation and R&D investment.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Dig	1.5555 *** (0.1739)	0.5930 *** (0.1061)	0.8672 *** (0.0904)	0.5261 *** (0.0748)	0.5588 *** (0.1230)	0.3824 *** (0.0833)
RDp						
RDh						
Pgdp		0.3949 *** (0.1355)		0.3444 *** (0.0886)		0.1507 * (0.0832)
Sout		0.4171 *** (0.0906)		0.2542 *** (0.0503)		0.1036 * (0.0585)
FDI		0.2006 ** (0.0839)		0.0174 (0.0397)		0.0689 (0.0787)
Tecm		0.1955 *** (0.0668)		−0.2346 *** (0.370)		−0.1690 *** (0.0328)
Constant	0.3593 *** (0.0944)	−1.2952 *** (0.2262)	0.2246 *** (0.0560)	−0.6144 *** (0.1493)	−0.0145 (0.0530)	−0.4529 *** (0.1439)
Control	N	Y	N	Y	N	Y
Region	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
R^2	0.8957	0.9616	0.9721	0.9840	0.9835	0.9874
N	240	240	240	240	240	240

Note: Robust standard errors in parentheses; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$. N and Y indicate whether the control variable is added or whether the fixed effect is used, where N represents no and Y represents yes.

5.2. The Influence of the Digital Economy on R&D Investment

The regression results are shown in Table 6; columns (3) and (4) show the regression results when the explained variable is R&D funds input. It can be observed that the digital economy significantly affects R&D funds at the 1% level with or without the inclusion of control variables. When no control variables are included, for every 1% change in the digital economy development index, a positive change of 0.8672% in R&D expenditure follows. After adding the control variables, for every 1% change in the digital economy development index, the R&D expenditure positively changes by 0.5261%. This indicates that the digital economy plays a positive role in R&D expenditure. The digital economy reduces the risk of asymmetric trading information and broadens the financing channels of enterprises. Enterprises can quickly obtain favorable information and make corresponding decisions, conform to the trend of policy development, reduce investments in risky projects, and seek reliable partners in a more transparent external market environment. For banks, on the other hand, big data technology can be used to evaluate enterprises and innovation projects more accurately so that capital can be directed to better innovation activities, which will not only encourage enterprises to focus on innovation activities but also improve the efficiency of market capital allocation and obtain innovation output to a greater extent with limited funds. In addition, the current government attaches great importance to green development, and financial support provides financial guarantee for enterprises' green innovation activities.

Columns (5) and (6) show the regression results when the explained variable is R&D personnel input. The results show that the effect of the digital economy on R&D personnel remains significant. When no control variables are included, every 1% change in the digital economy index is followed by a positive change of 0.5588% in R&D personnel input. With the inclusion of control variables, for every 1% change in the digital economy index, a positive change of 0.3824% in R&D personnel input follows. This indicates that the digital economy exerts a positive effect on R&D personnel input. Additionally, the application of digital technology leads to enterprises' low-end jobs gradually being replaced by machines, and the demand for high-end knowledge workers increases, which in turn optimizes the human capital structure of enterprises. It is also found that the R^2 becomes larger and the goodness of fit is enhanced after adding control variables.

The results of the control variables are in column (2); all control variables play a significant role in promoting regional green innovation. The index of regional economic development changes positively by 0.3949% at a significance level of 1% for every 1% change in the digital economy index. The level of regional economic development represents rich resources and good market environment, which is conducive to accelerating enterprise innovation. The expenditure on science and technology varies positively by 0.4171% at the 1% level, which shows that the government's attention and support to high-tech industries play a positive role in regional innovation. Foreign direct investment varies positively by 0.2006% at the 5% significance level, which reveals that the capital and technology brought by foreign investment have effectively helped corporate innovation. Finally, the level of the technology market changes positively by 0.1955% at the 1% significance level. Enterprises can find potential partners while purchasing technology in the technology market, and the flow of talents in the technology market also allows enterprises to find the high-tech talents they need and improve their innovation capability.

5.3. Mediating Effect Analysis

Considering the effects of both the digital economy and R&D investment on regional green innovation, the first two columns of Table 7 show the mediating effect of R&D funds and the last two columns show the mediating effect of R&D personnel. Here, we only discuss the regression results with the addition of control variables. The results in column (2) show that both the digital economy and R&D funds can improve regional green innovation, and the regression coefficient of the digital economy on green innovation is significantly smaller than 0.5930 after adding R&D funds, which indicates that R&D funds investment plays a mediating effect. The impacts of each 1% change in the digital economy and R&D funds on regional green innovation are 0.2286% and 0.6926%, respectively. The development of the digital economy promotes the investment of corporate research funds through improving the efficiency of financial services, which further boosts corporate green innovation technologies. The results in column (4) indicate that both the digital economy and R&D personnel investment improve regional green innovation capability, and R&D personnel play a mediating effect. The effects of each 1% change in digital economy and R&D personnel on regional green innovation are 0.3771% and 0.5647%, respectively. The above regression results further corroborate that the development of the digital economy promotes the investment of enterprises in research personnel. Since these personnel are senior professionals, they provide not ordinary labor but expertise in research and innovation, which can greatly improve productivity. Furthermore, we compared the degree of effect between R&D funds and R&D personnel and found that the digital economy has a more pronounced utility of enhancing R&D funds and a greater mediating utility of R&D funds than R&D personnel investment, which indicates that the funds input plays a greater role in promoting regional green innovation.

Table 7. Test of mediating effect of R&D investment.

Variable	(1)	(2)	(3)	(4)
Dig	0.5614 *** (0.1862)	0.2286 ** (0.0899)	0.9687 *** (0.1816)	0.3771 *** (0.1136)
RDp	1.1463 *** (0.1663)	0.6926 *** (0.1392)		
RDh			1.0500 *** (0.1895)	0.5647 *** (0.1711)

Table 7. *Cont.*

Variable	(1)	(2)	(3)	(4)
Pgdp		0.1563 *		0.3098 **
		(0.0900)		(0.1307)
Sout		0.2410 **		0.3586 ***
		(0.0977)		(0.0952)
FDI		0.1885 **		0.1616 *
		(0.0761)		(0.0935)
Tecm		0.3580 ***		0.2910 ***
		(0.0690)		(0.0716)
Constant	0.1018	−0.8696 ***	0.3745 ***	−1.0394 ***
	(0.0772)	(0.1508)	(0.0863)	(0.1971)
Control	N	Y	N	Y
Region	Y	Y	Y	Y
Year	Y	Y	Y	Y
R^2	0.9324	0.9692	0.9139	0.9656
N	240	240	240	240

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5.4. Regional Heterogeneity Analysis

Section 4.1 shows that there are different levels of digital economy and green innovation among the three regions in China, especially in the eastern region, where the number of green patents is far greater. Given the differences in digital finance, economic development, and information technology resources among the various regions in China, the impacts of the digital economy on green innovation may vary from region to region. In order to analyze the heterogeneity of the impacts in China, 30 provinces were divided into three parts: eastern China, central China, and western China. The results in Table 8 show that: whether in the eastern or mid-western regions, the digital economy has a significant positive effect on regional green innovation and R&D investment, but the degree of impact is different. Columns (1), (3), and (5) show the impacts of the digital economy on green innovation, R&D expenditure, and R&D personnel in the eastern region, respectively. Every 1% change in the digital economy index is followed by a positive change of 0.8505% in green innovation, 0.7885% in R&D expenditure, and 0.6140% in R&D personnel at the 1% significance level. Meanwhile, columns (2), (4), and (6) show that every 1% change in the digital economy index is followed by a positive change of 0.3901% in green innovation and 0.1622% in R&D expenditure at the 1% significance level and 0.0763% in R&D personnel at the 10% significance level. This indicates that the effects of digital economy on green innovation and R&D investment are significantly stronger in the eastern regions than in the central and western regions. The possible reasons are that the eastern region has abundant capital, high-tech talents, and an excellent market development environment whereas the economic development in central and western China is relatively slow, and the promoting effect of the digital economy in the latter regions is limited by factors such as technology and the environment, which reduce the promoting effect of the digital economy on green innovation.

Table 8. Regional heterogeneity analysis.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Dig	0.8505 ***	0.3901 ***	0.7885 ***	0.1622 ***	0.6140 ***	0.0763 *
	(0.1688)	(0.1119)	(0.1141)	(0.0324)	(0.1363)	(0.0441)
Pgdp	0.4748 ***	−0.2844 **	0.2876 **	0.1564 ***	0.1344	0.1631 ***
	(0.1710)	(0.1400)	(0.1080)	(0.0543)	(0.1029)	(0.0491)
Sout	0.2981 ***	0.9117 ***	0.2422 ***	0.2746 ***	0.0514	0.1389 ***
	(0.1084)	(0.1916)	(0.0603)	(0.0328)	(0.0737)	(0.0437)

Table 8. *Cont.*

Variable	(1)	(2)	(3)	(4)	(5)	(6)
FDI	0.1846	0.7147 **	−0.0659	0.6613 ***	0.0516	0.2786 ***
	(0.1107)	(0.3273)	(0.0686)	(0.1126)	(0.0886)	(0.0916)
Tecm	0.2412 ***	−0.1273	−0.2704 ***	−0.0932 ***	−0.1847 ***	−0.0902 **
	(0.0740)	(0.1251)	(0.0446)	(0.0325)	(0.0502)	(0.0425)
Constant	−1.2166 ***	0.3989 **	−0.4143 *	0.1959 ***	−0.3576 *	−0.1510 **
	(0.2909)	(0.1872)	(0.2113)	(0.0726)	(0.2065)	(0.0751)
Control	Y	Y	Y	Y	Y	Y
Region	Y	Y	Y	Y	Y	Y
Year	Y	Y	Y	Y	Y	Y
R^2	0.9736	0.8935	0.9838	0.9815	0.9865	0.9784
N	88	152	88	152	88	152

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5.5. Robustness Analysis

5.5.1. Endogeneity Test

Although the research uses fixed effects, it does not fundamentally avoid the omitted variable problem and the endogeneity problem caused by two-way causation. Specifically, the digital economy drives the development of regional green innovation through R&D investment, but green innovation also expands the demand for capital to a certain extent, which in turn promotes economic growth; thus, there is a clear two-way causal relationship between the digital economy and regional green innovation. In view of this, this paper further adopts the approach of finding an instrumental variable to address the endogeneity problem fundamentally. Finally, the digital economy index with a one-period lag was selected as the instrumental variable. On the one hand, the development of the digital economy itself will be influenced by the previous period, and the instrumental variable satisfies the requirement of relevance. On the other hand, the level of the digital economy in the lagged period cannot directly affect the innovation capability in the current period, which satisfies the requirement of exogeneity. This paper first uses the two-stage least squares (2SLS) method to verify the rationality of the instrumental variable. The results in Table 9 show that the regression coefficients of the models are significantly positive, and they pass the LM test for unidentifiable instrumental variables and the F test for weak instrumental variables. The F-value is 181.62, which is much larger than 10 and greater than the 10% threshold, indicating that there is no problem of weak instrumental variables. The reliability of the regression results was then verified. The last row of Table 9 reports the regression result of the instrumental variable on the digital economy, indicating that the level of the digital economy in the lagged period is closely related to the digital economy in the current period and positively varies at the 1% level of significance.

Table 9. Endogeneity test.

Variable	(1)	(2)	(3)
Dig	0.7909 ***	0.3421 **	0.7115 ***
	(0.1167)	(0.1558)	(0.1349)
RDp		0.6939 ***	
		(0.1418)	
RDh			0.2840 *
			(0.1470)
Constant	−2.9694 ***	−1.7131 ***	−2.7005 ***
	(0.2761)	(0.3823)	(0.3301)
Control	Y	Y	Y

Table 9. *Cont.*

Variable	(1)	(2)	(3)
Region	Y	Y	Y
Year	Y	Y	Y
R^2	0.9650	0.9728	0.9666
N	210	210	210
LM	108.78 (0.0000)		
Wald F	181.62		
10% threshold	16.38		
tool	1.0603 ***		

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5.5.2. Other Robustness Tests

To make the conclusions more reliable, the explained variable was replaced with the number of green utility model patent applications for analysis (Table 10). Green utility model patents are less innovative than green inventions but more innovative than design patents. Overall, the regression results remained robust. The development of the digital economy still effectively promotes regional green innovation at the 1% significance level, and the mediating effects of R&D funds and R&D personnel are also significant.

Table 10. Other robustness tests.

Variable	(1)	(2)	(3)
Dig	0.7373 *** (0.1424)	0.2670 *** (0.0948)	0.6007 *** (0.1735)
RDp		0.8936 *** (0.1530)	
RDh			0.3571 * (0.1894)
Pgdp	0.4365 *** (0.1619)	0.1286 (0.1071)	0.3826 ** (0.1739)
Sout	0.3029 *** (0.0890)	0.0757 (0.0828)	0.2659 *** (0.1001)
FDI	0.4173 *** (0.0804)	0.4017 *** (0.0547)	0.3927 *** (0.0964)
Tecm	−0.1894 *** (0.0619)	0.0201 (0.0520)	−0.1291 * (0.0778)
Constant	−1.6373 *** (0.2835)	−1.0882 *** (0.2008)	−1.4755 *** (0.3030)
Control	Y	Y	Y
Region	Y	Y	Y
Year	Y	Y	Y
R^2	0.9663	0.9790	0.9679
N	240	240	240

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

5.6. Further Analysis

The above research shows that the digital economy has a positive impact on the development of regional green innovation under certain conditions, which is mainly achieved by expediting the investment of human resources and R&D funds in R&D resources. However, existing research deems that the development of the digital economy has a nonlinear influence on regional innovation. Some scholars believe that the impact of the digital economy on regional innovation performance leads to marginal increases [77], while others believe that with the continuous improvement of the digital economy, the promoting effect of the digital economy on regional innovation capability gradually decreases [78]. However, it has not been discussed whether the digital economy has a nonlinear influence on the development of regional green innovation. Thus, this paper will further analyze the nonlinear influence of the digital economy by using the panel threshold model and explore the nonlinear relationship between the two.

In Tables 11 and 12, where regional green innovation is the explained variable and the digital economy index is the threshold variable, the threshold estimation results with the input of human resource as the explanatory variable are different from those with the input of R&D funds as the explanatory variable. When human resource input is the explanatory variable, the single threshold model is significant at the 5% level, while the double threshold model fails to pass the test. R&D expenditure as the explanatory variable did not pass the single threshold test. When the digital economy index is less than 1.6186, the coefficient of human resource input is 0.5365, whereas when the digital economy index exceeds 1.6186, the coefficient changes to 0.7487, and they are all significant at the 1% level. In the two stages, for every unit increase in human resource input, the regional green innovation will increase by 0.5365 and 0.7487 units, respectively. A possible reason is that the allocation of R&D resources is distorted in the early stage of digital economy development. As the effect of funds investment brought by the digital economy is stronger than that of human resource investment, the lack of R&D personnel matching with a large amount of R&D funds leads to the wasting of resources. Only when the corresponding level of human capital is reached can human resources give full play to their technology absorption effect effectively, so as to absorb excessive R&D funds and promote technological progress and efficiency improvement [79].

Table 11. Threshold test.

Explanatory Variables	Regional Green Innovation	Threshold Estimate	p	Times of BS	95% Confidence Interval
R&D funds	Single threshold	2.2298	0.6533	300	[2.0508, 2.3539]
R&D personnel	Single threshold Double threshold	1.6186 0.6767	0.0333 0.4467	300 300	[1.4238, 1.6237] [0.5283, 0.7031]

Table 12. Threshold regression coefficient and test.

R&D Personnel	Regional Green Innovation
Dig $\leq$ 1.6186	0.5365 *** (0.1043)
1.6186 < Dig	0.7487 *** (0.1039)
Control	Y
N	240
F	17.02
R^2	0.8450

*** $p < 0.01$.

6. Conclusions and Recommendations

This paper discussed the role and potential path of the digital economy in regional green innovation. Based on the panel data of 30 provinces, autonomous regions, and municipalities in China from 2011 to 2018, the relationship between the digital economy, R&D investment, and regional green innovation was tested through regression analysis and a fixed effect model. In addition, the threshold model was used to explore the nonlinear influence of the digital economy on regional green innovation. The specific findings are detailed below.

First, the digital economy can effectively promote regional green innovation. This paper tried to overcome certain endogeneity problems through the fixed effect technique and looking for an instrumental variable. The robustness of the conclusion was enhanced by replacing the explained variable.

Second, the development of the digital economy will increase the investment of scientific research funds and personnel and then accelerate the development of regional green innovation. R&D investment plays a partial mediating effect, which is consistent with the theoretical expectation. In the exploration of the conduction path, it was found that the output of capital input is larger than that of labor input, which highlights the urgency of research funds input.

Third, according to the regression results of regional heterogeneity, the digital economy has different promoting effects on the regional green innovation capability and R&D investment in various areas. The facilitating effect of the digital economy in eastern China is stronger than that in central and western China. This may be due to the R&D resources and green innovation capability in western China being restricted by technology, the environment, policies, and other factors, which reduces the promoting effect of the digital economy on the green innovation of enterprises.

Fourth, through further analysis, it was found that the digital economy has a significant nonlinear influence on the development of regional green innovation. This feature is mainly reflected in the influence of R&D personnel on regional green innovation. With the rising digital economy level, the number of R&D personnel also increases. When R&D personnel reach a certain level, the growth rate of regional green innovation will increase, which may be the result of the distortion of R&D resource allocation. Only when the level of human capital matches the R&D funds can human resources effectively absorb excessive R&D funds.

Based on the above conclusions, the following suggestions are put forward for local governments and enterprises. First, the development of the digital economy should continue to be promoted and the potential driving force of the digital economy for green innovation should be fully tapped into. In terms of digital technology, the construction scale of digital facilities should be reasonably expanded in accordance with regional absorption to avoid wasting of resources. Meanwhile, importance should be attached to network security and security protection technology should be used to encrypt data and protect information. In terms of the market environment, it is necessary to improve the formulation of intellectual property rights to protect enterprises' innovation achievements, maintain a sound economic and financial environment, and establish a fair and transparent supervision mechanism to encourage enterprises to give full play to their own advantages and reach a wider range of transactions and cooperation.

Second, green innovation technology should be optimized. The most effective and direct method is to increase the investment of scientific research funds and personnel. The government should actively formulate and publish policies to attract high-tech talents and introduce key technology leaders to the region. At the same time, subsidies to enterprises for green R&D innovation should be increased, tax relief measures should be implemented for related projects, and start-ups with weak foundations should be supported and equipped with basic digital technology facilities and sites for green R&D activities.

Third, various areas should implement differentiated development policies. For the eastern region, the good momentum of the digital economy should be maintained and it should take the lead in technological innovation. Information communication channels with neighboring areas should be established, and the green innovation development of neighboring areas should be promoted through knowledge exchange and talent flow. For the central and western regions, first of all, local governments and enterprises should find out the factors restricting their own development and make up for shortcomings. Meanwhile, they should attach importance to and cultivate local competitive industries and enhance the leading role of competitive industries.

Fourth, emphasis should be placed on the rational allocation of R&D resources. Enterprises and scientific research institutions need to consider the quantity and quality of R&D personnel, evaluate their work intensity and performance, and rationally allocate tasks for them so as to maximize innovation output. The local government should optimize the market environment of R&D resources, eliminate the unfavorable policy factors that restrict the effective allocation of resources, assess the growth space of innovation projects more reasonably, and allocate funds for them.

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