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Research on the Coordinated Development of Digital Economy, Green Technology Innovation, and Ecological Environment Quality—A Case Study of China

Xiaomei Li [1], Huchuan Deng [2], Xuanrui Yu [3], Jiehong Li [4] and Yang Yu [4,5,*]

1 College of Marxism, Chongqing Jiaotong University, 66 Xuefu Road, Chongqing 400074, China; 990202300003@cqjtu.edu.cn
2 College of Marxism, Southwest University, 2 Tiansheng Road, Chongqing 400715, China; dhchuan@hotmail.com
3 School of Civil Engineering, Chongqing University of Science and Technology, Chongqing 401331, China; yuxuanrui123@gmail.com
4 Centre for Infrastructural Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, High Street, Sydney, NSW 2052, Australia; jiehong.li@unswalumni.com
5 Multidisciplinary Center for Infrastructure Engineering, Shenyang University of Technology, Shenyang 110870, China
* Correspondence: yang.yu12@unsw.edu.au

Abstract: Based on panel data from 285 prefecture-level cities in China from 2019 to 2023, the synergistic effects of the digital economy, green technology innovation, and ecological environment quality were analyzed. First, using the entropy method, the measurement dimensions of the indicators of the digital economy, green technology innovation, and ecological environment quality were obtained. Second, employing a neural network model with these measurements as input variables, the interactive relationship among the digital economy, green technology innovation, and ecological environment quality was explored. Finally, based on the calculation results of the neural network model, the importance and impact of each input parameter on ecological environment quality were determined using weight analysis methods. The research findings indicate: (1) Utilizing the entropy method, the measurement dimensions of the indicators of the digital economy, green technology innovation, and ecological environment quality were obtained. Analysis of each indicator measurement reveals that environmental pressure has a significant impact on ecological environment quality, with significant differences in environmental pressure among different regions. Industrial digitization emerges as the core factor influencing the digital economy, being the most significant driving effect, followed by digital industrialization. Green technology innovation is crucial for promoting environmental protection and achieving high-quality green economic development. (2) Based on the neural network model, the interactive relationship among the digital economy, green technology innovation, and ecological environment quality was revealed. The results indicate that the digital economy has a direct impact on improving ecological environment quality. The relationship between the digital economy and the ecological environment exhibits nonlinear effects, with the rate of change in environmental pressure and environmental status measurements initially increasing significantly and then gradually slowing down as the measurement levels of digital industrialization and industrial digitization increase. Improvement in digital governance and data value measurement levels will contribute to enhancing environmental status and environmental governance levels. (3) Through weight analysis, it was found that in terms of direct effects, industrial digitization, and digital industrialization have the most significant impact on environmental pressure, with importance coefficients of 0.45 and 0.3, respectively, while data valorization has the least impact. Regarding intermediary effects, industrial digitization and green technology innovation have the most significant impact on environmental pressure, while digital governance and green technology innovation have a relatively clear impact on environmental status and environmental governance. These results lay the foundation for promoting the coordinated cooperation between the digital economy and green technology innovation and for advancing the establishment of a win–win situation between economic development and environmental protection.

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1. Introduction

Driven by rapid advancements in information technology, the digital economy's role in the national economy is becoming increasingly prominent. According to the "China Digital Economy Development Report (2023)" published by the China Academy of Information and Communications Technology, China's digital economy reached 50.2 trillion yuan in 2022, accounting for 41.5% of its GDP, becoming a key driving force for China's modernization [1]. China has now entered a new era of digital economy. Advanced digital technologies such as big data, blockchain, and the Internet of Things continuously innovate and reshape traditional production factors, profoundly impacting various sectors of society, effectively saving resources, mitigating environmental degradation, and alleviating resource constraints [2,3]. Alongside the development of the digital economy, efficient information exchange platforms ensure that innovative knowledge can be quickly and widely disseminated, accelerating the adoption of green technologies, opening new pathways for green technological innovation, and providing robust support for sustainable development [4]. The core of improving ecological environment quality lies in using technological innovation to enhance resource efficiency and strengthen environmental management capabilities. Therefore, at the current stage, the focus must be on innovation pathways driven by green technology. Compared to traditional technological innovations, green technological innovation, as a new type of technological innovation, emphasizes the role of technology in sustainable resource utilization, improving environmental quality, and promoting green development. It has the dual advantages of environmental protection and green economic benefits, contributing to the achievement of sustainable development goals [5].

Currently, the Chinese government has made certain progress in resolving the contradiction between rapid digital economic growth and environmental protection needs. The government has adopted a series of measures, including formulating a comprehensive set of environmental laws and policies, increasing support for green technology research and application, and encouraging environmentally friendly production and sustainable development. Additionally, the Chinese government actively promotes the integrated development of the digital economy and green technology, using digital means to enhance the efficiency of environmental monitoring, governance, and protection, therefore promoting the coordinated development of the digital economy and environmental protection. Moreover, the government has formulated a series of specific regulatory frameworks and policy interventions, such as the "Guiding Opinions on Promoting the Development of Green Technology Innovation", to guide enterprises to increase investment in green technology research and development and encourage the extensive application of green technology in the digital economy. The rapid development of information technology has highlighted the digital economy's growing role in the national economy, providing strong support for the coordinated development of the digital economy, green technology innovation, and ecological environment quality.

However, in the context of uneven economic development, less developed regions may face more severe environmental problems and resource shortages, limiting their development in the digital economy and green technology innovation fields. These regions may lack the necessary infrastructure, technological capacity, and financial support, leading to limited capabilities in environmental protection and green technology development. Additionally, lower development levels might make these regions more dependent on short-term economic growth, overlooking the importance of long-term sustainable development. In contrast, more developed regions may possess more resources and technological advantages, better supporting the development of the digital economy and green technology. These regions typically have more comprehensive infrastructure, advanced technology, and abundant talent reserves, allowing them to lead in green technology innovation and application. Furthermore, enterprises and governments in these regions are more likely to have sufficient funds to invest in environmental projects and green technology research and development, therefore promoting sustainable development. In contrast, more developed regions may have more resources and technical advantages, better supporting the development of the digital economy and green technologies. These regions typically have more comprehensive infrastructure, advanced technology, and a wealth of talent, enabling them to lead in green technology innovation and application. Additionally, enterprises and governments in these regions are more likely to have sufficient funds to invest in environmental projects and green technology research and development, therefore promoting sustainable development.

There is a close relationship between the digital economy, green technology innovation, and ecological environment quality. Scholars have explored the interaction mechanisms among these three aspects through theoretical research and empirical analysis to analyze the interaction mechanisms. For instance, El-Kassar et al. used micro-survey data from 215 companies and found through empirical analysis that the application of big data by enterprises influences their green innovation activities, which in turn affects their competitive advantage [6]. Goldfarb et al. [7] conducted preliminary explorations and analyses on the relationship between enterprise digitization and green technology innovation, suggesting that digitization can promote the transmission and exchange of environment-related information, therefore facilitating green technology innovation within enterprises. Cao et al. [8] argued from a theoretical perspective that the development of the digital economy can stimulate the innovation potential of information technology, therefore promoting green technology innovation and improving overall production efficiency. Eiadat [9] believed that green technology innovation and dissemination play a crucial role in the transformation and upgrading of manufacturing, promoting increased green consumption and driving green economic development. However, the effect of green technology innovation on green economic development is related to the region's original economic level. Mubarak [10] revealed the compatibility path between enterprise digitization and green sustainable development, helping to promote China's economic green transition and achieve "carbon peak" and "carbon neutrality" goals. Yang [11] built a green three-way interactive bridge among government, enterprises, and the public based on digital technology, promoting the development of the digital economy and ensuring ecological environment quality. Aaron and Jason [12] believed that the diffusion of the digital economy could reduce manufacturing costs and negative production externalities through constraint and incentive mechanisms, therefore protecting ecological resources and the natural environment. Samuel [13] argued from the perspective of enterprise production that financial development can lower the cost of enterprise financing and borrowing, supporting enterprises in technological research and development, which is conducive to improving environmental quality. Li [14] explained from an empirical analysis perspective the intrinsic connection between the digital economy and the ecological environment, proposing that the rapid growth of the digital economy helps to update traditional and relatively outdated production capacities, reduce environmental pollution, improve production efficiency, and thus enhance ecological support. Yuan [15] examined the impact of green technology innovation on carbon emissions at both provincial and urban levels, finding that green technology innovation significantly reduces carbon dioxide emissions. Walzl [16] analyzed the importance of technological innovation in promoting green sustainable development, suggesting that enterprises can reduce environmental pollution by improving their innovation capabilities to enhance energy efficiency, environmentally friendly energy supply technologies, material efficiency, and waste management. Chen [17] explored the interaction relationship between green technology and ecological civilization. From existing research, most scholars have, respectively, studied the interrelationships among the digital economy, green technology innovation, and ecological environment quality without integrating them into a unified research framework. The digital economy can drive the development of green technology, and the application of green technology can directly improve ecological environment quality. The interactions among these three aspects not only promote the development of the digital economy but also strengthen environmental protection and sustainable development. Furthermore, it helps to find a balance between economic growth and environmental protection.

2. Literature Review

To explore the interrelationships among the digital economy, green technology innovation, and ecological environment quality, scholars have conducted in-depth research. In summary, the research mainly focuses on three aspects:

In the context of the relationship between the digital economy and green technology innovation, scholars have primarily investigated how digitalization can promote the development and application of green technologies. He [18] and Dou [19] analyzed the impact of the digital economy on green technology innovation within enterprises, suggesting that the digital economy provides strong technological support and platforms for green technology innovation, therefore promoting both the quality and quantity of such innovations. Wang [20], based on panel data from 274 prefecture-level cities in China and using modeling analysis methods, explored the effects of the digital economy on green technology innovation, finding that the digital economy effectively enhances the output of green technology innovation. Thompson [21] argued that the development of the digital economy digitizes production factors and utilizes big data and artificial intelligence to shorten supply chain lengths, improve supply chain efficiency, reduce enterprise costs, and increase profitability. The improvement in profitability encourages enterprises to allocate more idle resources for independent technological research and development, effectively promoting the level of technological innovation. Furthermore, the gradual improvement of digital infrastructure significantly enhances the frequency of innovation, the diffusion of technological innovation, the cultivation of high-end production factors, and the optimization reform of production processes, therefore greatly enhancing industrial production efficiency and response speed [22]. The digital economy leverages big data technology to improve resource allocation, transform industrial structures, and drive innovation and development in green technologies.

In research on the relationship between green technology innovation and the ecological environment, Lee [23] and Acemoglu [24] argue that innovation driven by green technology progress is an effective means to address environmental pollution issues such as carbon emissions. Zhang [25], using empirical analysis methods, explored the positive impact of green technology innovation on ecological efficiency. Liu [26] analyzed the significant impact of technological progress on haze pollution, finding that technological innovation not only reduces haze pollution but also lowers unit energy consumption and emissions, effectively mitigating atmospheric pollution. Yuan [15] examined the impact of green technology innovation on carbon emissions at the provincial and city levels, discovering that green technology innovation significantly reduces carbon dioxide emissions. Clearly, green technology innovation promotes the adoption of clean and efficient energy solutions, reducing dependence on fossil fuels and, therefore, lowering greenhouse gas and other pollutant emissions. This not only promotes efficient resource utilization and recycling, reducing reliance on new resources and waste generation but also provides a new path for sustainable development to society.

Regarding the relationship between the digital economy and the ecological environment, the digital economy significantly enhances production efficiency and energy resource utilization by effectively integrating digital technologies with traditional industrial production activities [27,28]. It plays a crucial role in achieving sustainable development. Kunkel [29] and Wen [30] explored the driving role of the digital economy in ecological protection. Research indicates that the digital economy, through enhancing energy utilization efficiency and improving energy allocation, can achieve the goal of protecting the ecological environment. Additionally, by improving resource utilization efficiency and adjusting existing industrial structures, the digital economy promotes the development of low-carbon industries, therefore reducing pollutant emissions. Li [31] and Zhu [32], using modeling analysis methods, revealed the causal effects and transmission mechanisms between the digital economy and environmental pollution. The results show that the growth of the digital economy effectively unleashes innovation-driving forces, promotes changes in industrial production and daily lifestyles, and consequently reduces emissions of major pollutants such as sulfur dioxide. Aaron [12] pointed out that the knowledge spillover effect of the digital economy optimizes and reduces manufacturing costs within the industrial system, enhances connections and responsiveness to the external environment, and achieves goals of ecological environment governance and resource protection during the technological innovation process. Thompson [21] argued that through continuous innovation in the digital economy, digital technologies drive the construction of platform functions and the creation of multi-dimensional scenarios, optimize resource allocation processes, and reduce inefficient and unnecessary resource waste.

It can be seen that the digital economy not only plays an important role in improving the ecological environment and reducing carbon emissions but also has a profound impact on promoting industrial upgrading and lifestyle transformation, which is crucial for achieving sustainable development goals.

In summary, scholars have conducted detailed analyses and explanations of the relationships between the digital economy, green technology innovation, and ecological environment quality through theoretical and empirical analyses. They have revealed the intrinsic connections between the digital economy and green technology innovation, green technology innovation and ecological environment quality, as well as the digital economy and ecological environment quality. However, studies on the interaction mechanisms and symbiotic relationships among these three factors are rare. The digital economy, green technology innovation, and ecological environment quality should be viewed as a unified, organic whole, susceptible to various random factors and characterized by complex nonlinearity. Describing the interaction mechanisms among these three factors requires more sophisticated methods beyond one-time transformations and traditional linear regression models.

With the development of computer technology, neural network models have been widely used to predict economic development, changes in environmental pollution, and risk assessment of economic environments [33–36]. These problems share a common characteristic: the relationships between variables are complex, highly stochastic, and exhibit nonlinear responses. Similarly, the process of digital economy development regulating the ecological environment by promoting green technology innovation is highly complex, akin to the challenges faced in predicting economic development and assessing economic environmental risks. The key to understanding the interaction mechanism lies in revealing the complex nonlinear relationships among variables. Neural network models not only learn complex and nonlinear relationships between inputs and outputs through their multi-layer structures and activation functions but can also adapt to different types of data and tasks by adjusting network architectures (such as the number of layers, neurons, and connection patterns). Furthermore, neural network models exhibit good generalization capabilities and strong fault tolerance. Through appropriate training, neural networks can generalize to unseen data and tolerate noise and missing values in input data to a certain extent, allowing them to address problems that traditional linear models cannot handle [37].

Therefore, this study establishes a corresponding indicator system for these three factors, using the digital economy as the input variable, green technology innovation as the mediating variable, and ecological environment quality as the output variable. It applies a neural network model to reveal the interaction patterns among them. Additionally, through weight analysis, this study elucidates the impact patterns of the digital economy and green technology innovation on improving environmental quality, identifies relevant important parameters, and provides both theoretical significance and practical value.

Research Significance

Compared with existing published materials, this paper uses empirical analysis methods and a neural network model, with indicators such as the digital economy and green technology innovation as input variables and ecological environment quality as the output variable, to reveal the nonlinear development relationship between them. It clarifies their synergistic effects and analyzes the significance of each input parameter's impact on ecological environment quality based on the weight analysis method, effectively addressing a major gap in existing theoretical research. The objective of this study is to provide a comprehensive approach that uncovers the intrinsic relationships between the digital economy, green technology innovation, and ecological environment quality. This not only aids in promoting sustainable development and enhancing the scientific basis of policymaking but also facilitates industrial upgrading and structural optimization, drives technological innovation and application, improves the technological competitiveness of a country or region, and finds new ways to improve ecological environment quality, therefore providing theoretical support and practical guidance for achieving sustainable development.

3. Theoretical Analysis and Research Hypotheses

Improving ecological environment quality is an inherent requirement for advancing harmonious coexistence between humans and nature, involving various fields of economic and social development. By leveraging its core advantages in cross-temporal and spatial information dissemination, data generation and sharing, and reducing transaction costs, the digital economy effectively addresses the challenges faced in the ecological environment domain. This paper will comprehensively explore the impact mechanism of the digital economy on the ecological environment and propose research hypotheses.

3.1. Analysis of the Direct Effects of the Digital Economy on Promoting the Improvement of Ecological Environment Quality

The continuous development of the digital economy not only contributes to optimizing resource allocation and production processes, enhancing energy efficiency, but also strengthens real-time environmental monitoring and protection capabilities, drives green consumption, and the green upgrade of traditional industries, playing a crucial role in improving ecological environment quality. First, the development of the digital economy provides robust support for optimizing resource allocation. Leveraging technologies like big data analysis, cloud computing, and intelligent analysis and prediction, the digital economy efficiently manages and allocates energy resources, therefore improving energy efficiency and reducing environmental burdens [38]. Second, the growth of the digital economy enhances the efficiency of environmental monitoring and protection. Digital technologies such as remote sensing and AI monitoring enable real-time monitoring of air quality, water quality, and forest fires, leading to more timely protection of the ecological environment and reduction of environmental pollution and damage [39]. Additionally, the development of the digital economy drives green consumption. Through e-commerce platforms, social media, and other means, the digital economy promotes the popularity of green products and services. Consumers access environmental information about products through digital platforms, enhancing awareness and understanding of eco-friendly products, therefore stimulating the growth of green consumption [40]. Finally, the development of the digital economy promotes the green upgrade of traditional industries. Digital transformation, by introducing advanced data analytics and machine learning algorithms, helps enterprises optimize production processes, forecast market demand, improve resource utilization efficiency, and reduce environmental pollution emissions [41,42]. Simultaneously, digital technologies such as 3D printing and computer-aided design (CAD) assist enterprises in designing and producing more environmentally friendly products, effectively reducing development costs and time and enabling enterprises to adopt eco-friendly materials and designs.

Hypothesis 1. *The development of the digital economy significantly promotes the improvement of ecological environment quality.*

3.2. Nonlinear Spillover Effects of the Digital Economy on Enhancing Ecological Environment Quality

In the era of the digital economy, the relationship between the development of the digital economy and the improvement of ecological environment quality exhibits complex nonlinear characteristics, influenced by various factors such as technological advancements, digital industrialization, industrial digitization, and digital governance, which collectively contribute to fluctuations in environmental impact. On one hand, advancements in digital technologies such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics enable governments and businesses to more effectively monitor and manage resource consumption, therefore enhancing energy efficiency. On the other hand, the implementation of digital governance also faces challenges, as its development relies on extensive data centers and network infrastructure [43], closely tied to the rapid development of science and technology, which is crucial for achieving digital economic growth. However, overinvestment of resources in technological solutions may impact other direct environmental protection and social development initiatives. Furthermore, the development of digital industrialization and industrial digitization can improve production efficiency, increase innovation and competitiveness among enterprises, and open up new business models. Yet, challenges such as substantial skills transformation and issues related to data misuse also emerge. In summary, while the development of digital industrialization and industrial digitization presents significant opportunities for the digital economy, it also comes with challenges and risks. Successful digital transformation requires enterprises and governments to adopt appropriate strategies and measures to maximize the benefits of digital technologies while addressing potential adverse impacts.

Hypothesis 2. *The impact of the digital economy on enhancing ecological environment quality exhibits nonlinear characteristics.*

3.3. Conduction Mechanism of the Digital Economy's Impact on Enhancing Ecological Environment Quality

The environmental protection characteristics of technology are the key foundation for achieving economic growth and improving environmental quality, with green technology innovation playing a crucial role in realizing economic growth and environmental quality improvement [44]. First, the widespread application of green technology innovation promotes the development of digital technologies, enhances production intelligence, increases enterprise productivity, and reduces overreliance on natural resources, therefore improving the ecological environment and achieving sustainable resource utilization. Second, green technology innovation helps reduce pollution emissions. Traditional industrial production processes often result in significant pollutant emissions, while green technology, promoted in the development of the digital economy, drives the advancement of clean and renewable energy technologies [45]. Lastly, green technology innovation drives economic transformation and upgrading, promoting sustainable development. As green technology is applied in the digital economy, green industries are becoming a new engine for economic growth, driving optimization and transformation of economic structure and providing new impetus and support for sustainable development.

Hypothesis 3. *The digital economy positively influences the enhancement of ecological environment quality through green technology innovation.*

4. Research Design

Hypothesis 1 suggests that the development of the digital economy significantly promotes the improvement of ecological environment quality. To measure the extent of improvement in ecological environment quality, we may select relevant indicators such as environmental pressure, environmental status, and environmental governance. These indicators can reflect the health of ecosystems, therefore assessing the impact of digital economy development on the environment. Hypothesis 2 proposes that the impact of the digital economy on enhancing ecological environment quality exhibits nonlinear characteristics. To test this hypothesis, we may choose indicators reflecting the level of digital economy development, such as digital industrialization, industrial digitization, digital governance, and data monetization. Then, we can study the nonlinear relationship between these indicators and ecological environment quality using neural network algorithms. Hypothesis 3 indicates that the digital economy positively influences the enhancement of ecological environment quality through green technology innovation. To verify this hypothesis, we need to select indicators reflecting the level of green technology innovation, such as the number of patents granted. Then, we can analyze the correlation between these indicators and ecological environment quality to confirm whether the positive impact of the digital economy on ecological environment quality is related to green technology innovation. Next, we will explain how to calculate these indicators and integrate them into our neural network model. First, data collection is a crucial step in research methodology. We need to collect data related to digital economy development, ecological environment quality, and green technology innovation, including historical and latest data. The preprocessing stage involves steps such as data cleaning, handling missing values, and detecting outliers to ensure data quality and availability. Second, to ensure the effectiveness and accuracy of the research results, we analyze the measurement dimensions of each indicator related to the digital economy, green technology innovation, and ecological environment quality using the entropy method. We then extract relevant features and use them as input features for the model. Finally, we use a neural network model to analyze the data and validate our hypotheses. The neural network model can predict the impact of digital economy development on ecological environment quality and further explore the nonlinear characteristics and effects of green technology innovation. Based on the weight analysis method, we clarify the importance of each parameter. This analytical framework aims to explore in depth how the digital economy indirectly influences ecological environment quality through green technology innovation and the dynamic relationship between this impact and different hierarchical indicators.

4.1. Indicator Selection

The coordinated advancement of the digital economy, green technology innovation, and ecological environment quality is a complex process involving multiple systems and variables, with interactions among variables influenced by various factors. Analyzing individual indicators cannot fully assess the overall development status of each variable. Therefore, it is particularly important to conduct comprehensive evaluations of the digital economy, green technology innovation, and ecological environment quality by constructing a multi-indicator system.

(1) Digital Economy: Drawing on the "Four Digitalizations" framework developed by the China Academy of Information and Communications Technology (CAICT) and based on the research of literature [46], we examine the digital industry across four dimensions: digital industrialization, industrial digitalization, digital governance, and data value realization. The specific measurement indicators include digital industry practitioners, the telecommunications industry, the electronic information manufacturing industry, the broadcasting and television industry, the internet, and related services, as detailed in Table 1.

Table 1. Measurement indicator system for the digital economy.

Primary Indicator	Secondary Indicator	Indicator Meaning
DI	Telecommunications industry	Proportion of employees in computer services
	Internet and related services industry	Number of publicly traded internet and related services companies
	Software industry	Publicly listed software services companies
ID	Digital agriculture	Number of agricultural and rural informatization demonstration bases
	Industrial digitization	Number of publicly listed companies in the smart business sector
	Service industry digitization	Service consumption index
	Digitalization of business	Digital inclusive finance index
DG	Digital user penetration	Number of Internet broadband subscribers
	Digital government and smart city	Government website index and smart City Pilots
DV	Transaction volume	Number of data trading agencies
	Data openness	Number of government data open platforms

Notes: DI means digital industrialization, ID means industrial digitization, DG means digital governance, DV means data monetization.

(2) Green Technology Innovation: Arundel et al. argue that patent grants are the most common and reliable measure of technological innovation [47]. Following the approach of Fan [48] and based on the classification method outlined in the "China Green Patent Statistical Report" published by the Planning and Development Department of the State Intellectual Property Office, we collected green patent data from various cities through the State Intellectual Property Office's patent platform. We used the number of green invention patent applications per 10,000 people to assess the scale of green technology innovation and evaluate the level of green technology innovation.

(3) Ecological Environment Quality: This article draws on Han's [49] research on the measurement of ecological environment quality to construct a comprehensive ecological environment quality index system comprising pressure, state, and governance dimensions. The calculation indicators include industrial SO_2 emissions, industrial wastewater discharge, industrial particulate matter emissions, urban green coverage rate (%), per capita green space area, comprehensive utilization rate of industrial solid waste, per capita industrial dust removal, and urban industrial wastewater treatment rate, as shown in Table 2.

Table 2. Ecological environment quality measurement index system.

Primary Indicator	Secondary Indicator
Environmental pressure	Industrial SO_2 emissions (10,000 tons) Industrial wastewater discharge (billion tons) Industrial particulate emissions (10,000 tons)
Environmental condition	Urban green coverage rate (%) Per capita green space area (square meters)
Environmental governance	Comprehensive utilization rate of general industrial solid waste (%) Per capita removal of industrial smoke (dust) (tons/person) Treatment rate of industrial wastewater in urban areas (%)

4.2. Model Design

Based on the above analysis, the following model is constructed to explore the influence of secondary indicators on primary indicators of the digital economy, green technology innovation, and ecological environment quality. First, each indicator is positively standardized according to Equation (1) to ensure comparability between indicators.

$$X_i = \frac{X_i - \min(X_i)}{\max(X_i) - \min(X_i)} \quad (1)$$

Next, calculate the weight of each indicator using the following formula:

$$\omega_i = \frac{X_i}{\sum_{t=1}^{m} X_i} \quad (2)$$

On this basis, calculate the entropy e_i of each indicator using the following formula:

$$e_i = \frac{-1}{\ln m} \sum_{t=1}^{m} \omega_i \cdot \ln \omega_i \quad (3)$$

Calculate the redundancy of information entropy.

$$d_i = 1 - e_i \quad (4)$$

The measurement of selected indicators can be represented as follows:

$$W_i = d_i / \sum_{t=1}^{m} d_i \quad (5)$$

The computation of the indicators for the digital economy, green technology innovation, and ecological environment quality is completed, and a neural network model is employed to reveal the interaction among them. The calculation of the entire model consists of two parts: forward propagation and backward propagation. Forward propagation includes the propagation from the input layer to the hidden layer and from the hidden layer to the output layer. The form of propagation from the input layer to the hidden layer can be represented as follows:

$$a_j = f\left(\sum_i w_{ij} x_i + b_j\right) \quad (6)$$

where x_i represents the input variables (such as indicators related to the digital economy and green technology innovation), ω_{ij} represents the weight parameters from the input layer to the hidden layer, b_j represents the bias term of the j-th neuron in the hidden layer, and f represents the activation function. The propagation form from the hidden layer to the output layer can be represented as follows:

$$y_k = f\left(\sum_i w_{jk} a_j + b_k\right) \quad (7)$$

where y_k represents the predicted result of the model, ω_{jk} represents the weight parameters from the hidden layer to the output layer, and b_k represents the bias term of the k-th neuron in the output layer.

The backward propagation of the model involves two aspects: calculating the model output error and backpropagating the error. The calculation method of the model output error is represented as follows:

$$\delta_k = (y_k - t_k) \times f'(z_k) \quad (8)$$

where: δ_k represents the error result of each neuron, t_k is the true value, and $f'(z_k)$ represents the derivative of the activation function. The calculation process of the model's backpropagation error is as follows:

$$\delta_j = \left(\sum_k w_{jk}\delta_j\right) \times f'(z_k) \quad (9)$$

where: δ_j represents the backpropagation error for the j-th neuron. The entire calculation process of the neural network model is illustrated in Figure 1. Based on the weight calculation results between the input layer and the hidden layer, as well as between the hidden layer and the output layer, the importance of each input parameter to the output parameter can be determined. The calculation method is shown in Equation (10):

$$Z_{ik} = \frac{\sum_{j=1}^{L}\left(\frac{w_{ij}}{\sum_{r=1}^{N} w_{rj}} v_{jk}\right)}{\sum_{i=1}^{N}\left(\sum_{j=1}^{L}\left(\frac{w_{ij}}{\sum_{r=1}^{N} w_{rj}} v_{jk}\right)\right)} \quad (10)$$

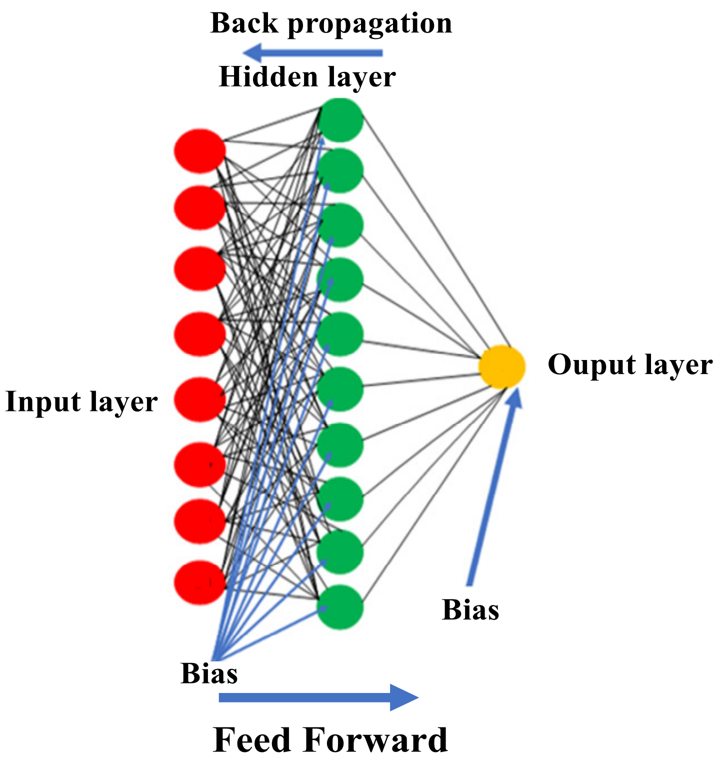


Figure 1. Calculation process of the neural network model.

5. Empirical Analysis

5.1. Data Source and Analysis

This study selected 285 prefecture-level cities in China as research samples (excluding cities with a high number of missing values or inconsistent time series data, such as Chaohu, Sansha, Danzhou, Bijie, Tongren, and Haidong). The sample data were sourced from the China Statistical Yearbook, China City Statistical Yearbook, China Energy Statistical Yearbook, China Environmental Yearbook, as well as provincial statistical yearbooks, the China National Research Data Sharing Platform (CNRDS) listed company database, and research reports on China government website development. Table 3 displays the calculated results for each variable measurement.

Table 3. Descriptive statistics of main variables.

Variable Type	Variable	Mean	Variance	Minimum	Maximum
Dependent variable	Environmental Pressure	0.34	0.20	0.05	0.47
	Environmental State	0.23	0.15	0.08	0.31
	Environmental Governance	0.15	0.02	0.05	0.19
Independent variable	Digital Industrialization	0.35	0.18	0.01	0.53
	Industrial Digitalization	0.37	0.12	0.03	0.47
	Digital Governance	0.12	0.08	0.03	0.174
	Data Monetization	0.11	0.03	0.03	0.195
Mediator variable	Green technology innovation	0.23	0.12	0.003	1.03

The data from Table 3 shows that the mean value of environmental pressure is the highest among ecological environmental quality indicators, indicating a significant impact of environmental pressure on ecological environmental quality. Additionally, the large variance of the environmental pressure variable suggests considerable differences in environmental pressure among different regions. In relatively developed areas such as Shanghai and Shenzhen, the environmental pressure index remains relatively low, around 0.08, mainly due to the development of high-tech and green industries with high resource utilization efficiency and relatively low pollution emissions, thus providing a certain level of environmental protection. Conversely, in regions like Shanxi, Jilin, and Hebei, economic development heavily relies on energy and traditional manufacturing industries, resulting in significant environmental pollution and evident environmental pressure indexes generally exceeding 0.38, well above the national average. Cities with the lowest environmental pressure indexes include Dali, Guilin, and Qinghai, where urban GDP growth is primarily driven by the tourism industry. These cities prioritize environmental protection through government actions, resulting in lower environmental pressure.

In the field of digital economy, industrial digitization is its core driving factor, exerting the most significant impact on the digital economy, followed by digital industrialization. This phenomenon is facilitated by advancements in information and communication technology (ICT), which not only enhance the productivity and service quality of traditional industries but also give rise to new industry forms and business models, optimizing and upgrading economic structures. Moreover, industrial digitization breaks geographical barriers, enabling enterprises to reach global markets and greatly promoting cross-border trade and international cooperation, thus further driving the development of the digital economy. However, there are significant differences in industrial digitization among cities nationwide. Coastal cities like Shanghai and Shenzhen adopted digital industry forms and business models early, advancing the development of industrial digitization. In contrast, cities in central and western Chinese regions have relatively lower levels of informatization, with digital industry forms and business models still in their infancy. Additionally, digital governance and data valorization exhibit small means and variances, indicating that the efficiency of Chinese provincial and municipal digital transformation is not high, and the potential value of data remains largely untapped.

Green technology innovation plays a crucial role in addressing global environmental challenges and achieving sustainable development goals. It involves the development and application of new technologies and methods to reduce environmental impacts, improve resource efficiency, and promote sustainable economic and environmental development. From the statistical results, it is evident that cities across China still have many shortcomings in green technology innovation and require further improvement. Particularly in Chinese central and western regions, green innovation technology is vital for sustainable economic and environmental development. Regarding environmental protection, green technology innovation not only enables efficient resource utilization and recycling to reduce waste and protect natural resources but also facilitates the development of cleaner and more efficient products, directly contributing to reducing air, water, and soil pollution and lowering harmful emissions. In terms of economic development, the development and application of green technology can create new industries and job opportunities, stimulate economic growth, and ensure a more sustainable economic development path.

In summary, the analysis of environmental quality, digital economic development, and green technology innovation reveals the current status and challenges faced by China in environmental protection, economic digital transformation, and the application of green technologies. First, the analysis of environmental pressure indices demonstrates a significant impact of environmental pressure on ecological quality, with noticeable variations among different regions. Relatively developed areas such as Shanghai, Shenzhen, and others exhibit lower environmental pressure due to the development of high-tech and green industries, whereas regions reliant on energy and traditional manufacturing industries, such as Shanxi, Jilin, and Hebei, face higher environmental pressures. This underscores the critical role of optimizing and transforming industrial structures to alleviate environmental pressures. Second, industrial digitization, as the core driving force of the digital economy, plays a decisive role in improving production efficiency and fostering innovation in new industrial forms and business models. However, there are significant disparities in the progress of industrial digitization among domestic cities. Coastal cities, having formed digital industries and business models earlier, have accelerated the development of industrial digitization, whereas cities in central and western China, with lower levels of informatization, face substantial challenges in digital transformation. Lastly, green technology innovation is crucial for promoting environmental protection and achieving high-quality green economic development. Despite some progress in green technology innovation in China, particularly in central and western cities, there remains substantial room for improvement in the application and innovation of green technologies. This calls for increased investment in green technology research and development to drive the development of green industries and achieve efficient resource utilization and sustainable environmental development. In conclusion, addressing these current conditions and challenges requires comprehensive strategies to strengthen industrial structure adjustments, advance digital transformation, and promote green technology innovation. These efforts aim to improve environmental quality, achieve high-quality green economic development, and facilitate comprehensive societal progress.

5.2. The Direct Effect of the Digital Economy on the Improvement of Ecological Environmental Quality

To investigate the direct effect of the digital economy on the improvement of ecological and environmental quality, this study theoretically elaborates on the direct effect of the digital economy on promoting high-quality ecological development based on a neural network model with four dimensions as input variables: digital industrialization, industrial digitalization, digital governance, and data monetization, and three output variables: environmental pressure, environmental state, and environmental governance. The model-solving steps are as follows: first, the dataset of each input parameter is divided into two sets, named the training set and the testing set, using random sampling. To ensure computational accuracy and speed, the model is designed with one hidden layer containing 10 neurons. The calculations are implemented using the MATLAB v.2022b computing platform. The computational results are shown in Figure 2.

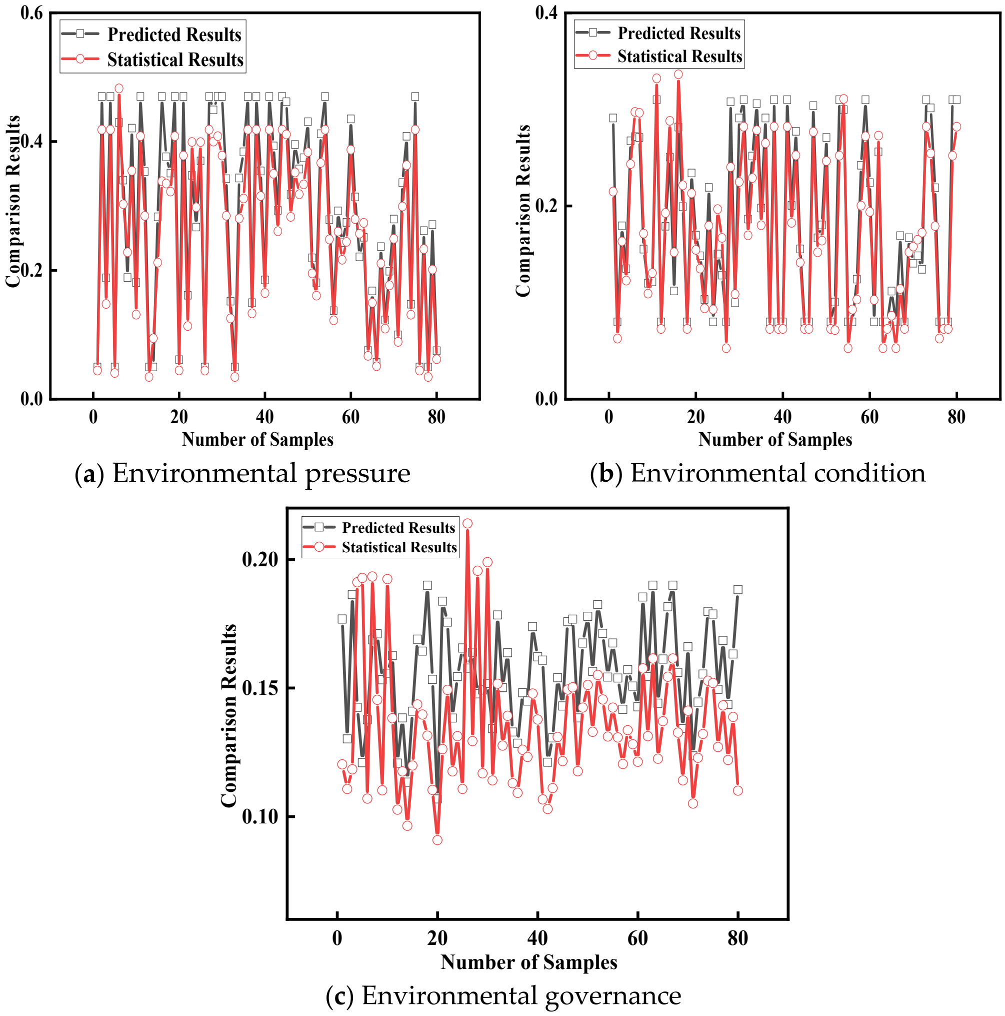


Figure 2. Comparative Prediction Results of the Neural Network Model.

Based on the prediction results shown in Figure 2, the residual values and relative error values between the predicted values and the statistical results were calculated, and the obtained results are presented in Figure 3.

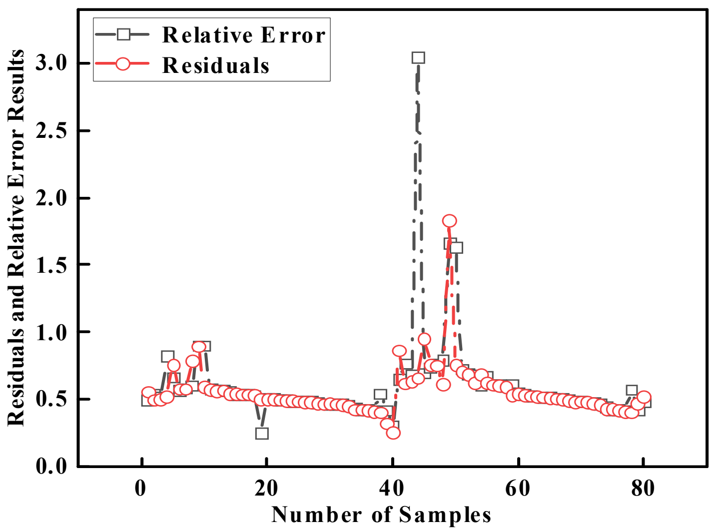


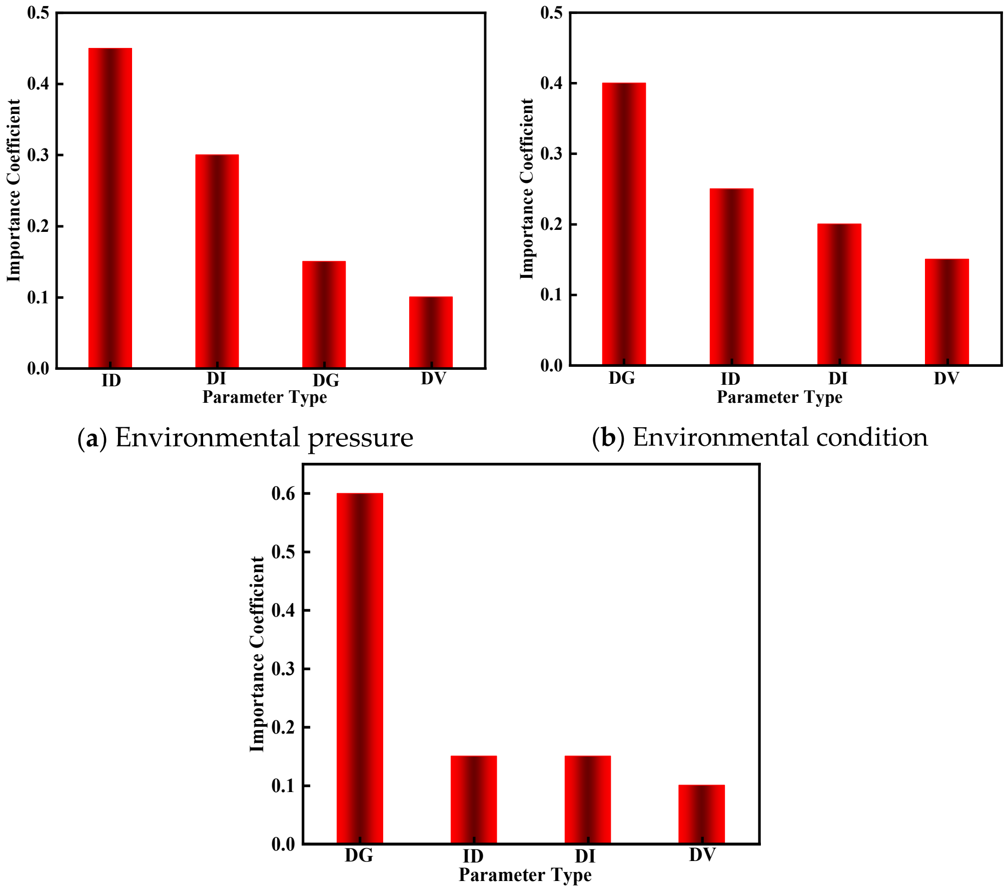
Figure 3. Calculation results of relative error and residual.

Further analysis of the results presented in Figures 2 and 3 reveals that the predicted trends align well with the actual outcomes, indicating that the BP neural network can effectively analyze the interrelationships between the digital economy and the ecological environment. Additionally, based on the results shown in Figure 2, it is evident that the measurement level of environmental pressure indicators in ecological environmental quality is relatively high, suggesting that Chinese cities still face significant environmental pressures. This is likely due to the generation of large amounts of pollutants such as exhaust gases, wastewater, and solid waste during the processes of industrialization and urbanization. Therefore, it is necessary to strengthen environmental management and monitoring and implement more effective measures to reduce pollutant emissions, protect the ecological environment, and ensure the health and quality of life of the people. Furthermore, the measurement level of environmental governance is relatively low, indicating that we have not yet reached the standards required for environmental pollution control. Although the government has implemented a series of environmental protection policies and measures, there are still issues, such as lax supervision and enforcement in practice. Therefore, it is essential to further strengthen the environmental management system, enhance supervision and enforcement efficiency, increase investment in environmental protection, and promote greater progress in environmental governance efforts.

In summary, to achieve sustainable economic development and continuous improvement of the ecological environment, it is crucial to not only accelerate the development of the digital economy but also further enhance public awareness of environmental issues and implement proactive and effective measures. Together, we can promote the construction of ecological civilization and provide a better living environment for people.

Based on the weight analysis between the input layer and hidden layer, as well as between the hidden layer and output layer of the neural network model, and according to Equation (10), the importance of input parameters on the output parameters can be calculated. The results are shown in Figure 4.

As shown in Figure 4, it can be observed that for environmental pressure, industrial digitalization and digital industrialization have the most significant impacts, with importance coefficients of 0.45 and 0.3, respectively, while data monetization has the least impact. The reasons are as follows: on one hand, the application of digital technology enables the production process to be more intelligent and precise, therefore improving resource utilization efficiency. For example, digital monitoring and optimization of production equipment can reduce energy and raw material waste, as well as pollution emissions and waste generation during production. On the other hand, the application of digital technology enables more precise and efficient environmental monitoring and governance. Through real-time monitoring and data analysis, environmental pollution sources and problem areas can be promptly identified, allowing for quicker adjustments and governance measures to reduce environmental pressure and risks. Moreover, the widespread use and application of digital technology also helps raise public awareness of environmental protection. Through digital media and educational platforms, environmental issues and solutions can be visually presented, fostering participation and support from various sectors of society and driving the development of environmental protection initiatives. Therefore, industrial digitalization and digital industrialization have a more significant impact on environmental pressure. Regarding environmental conditions and environmental governance, digital governance has the most significant impact. First, digital governance enables timely detection of environmental pollution and resource wastage through real-time monitoring of environmental data, facilitating faster responses and mitigation measures. Second, through digital platforms, comprehensive public disclosure and sharing of environmental information can be achieved, enhancing public understanding and involvement in environmental issues. Additionally, digital technology provides the public with channels and tools for participating in environmental governance, fostering cooperation and communication among the public, government, and businesses, therefore facilitating the smooth implementation of environmental governance efforts. Lastly, digital governance enhances the efficiency and quality of environmental governance. Through digital technology, automation of environmental data collection, analysis, and processing reduces human and time costs, improving the efficiency of environmental governance. Furthermore, digital technology contributes to the informatization and intelligence of governance processes, enhancing the scientific accuracy and level of environmental governance decision-making.



(**a**) Environmental pressure (**b**) Environmental condition

(**c**) Environmental governance

Figure 4. Analysis Results of Importance of Each Parameter.

In summary, digital technology has had a significant impact on environmental pressure, environmental conditions, and environmental governance through industrial digitalization, digital industrialization, and digital governance, providing crucial support for promoting environmental protection and sustainable development. First, through industrial digitalization and digital industrialization, production processes have become more intelligent and refined, effectively improving resource utilization efficiency and reducing energy consumption and emissions. This not only reduces adverse environmental impacts but also enhances production efficiency and competitiveness, achieving a win–win situation for economic growth and environmental protection. For example, the digital monitoring and optimization of production equipment can reduce energy and raw material waste, lower pollution emissions, and decrease waste generation during the production process, therefore alleviating environmental pressure. At the same time, the application of digital technology enables enterprises to better manage and monitor their supply chains, achieving greener and more sustainable supply chains. Second, the implementation of digital governance has enhanced the capabilities of environmental monitoring and management. Through real-time monitoring, data analysis, and intelligent decision-making, environmental issues can be promptly detected and addressed, improving the precision and efficiency of governance. For example, sensor and Internet of Things (IoT) technologies can continuously monitor environmental parameters such as air quality, water quality, and soil pollution. Using big data analysis, pollution sources can be quickly identified, and effective measures can be taken to remediate them. Digital platforms facilitate the comprehensive disclosure and sharing of environmental information, increasing public understanding and participation in environmental issues. The public can access environmental data and governance information through these platforms, enhancing their environmental awareness and actively participating in environmental protection efforts. Digital technology also provides the public with channels and tools for participating in environmental governance, promoting collaboration and communication among the public, government, and enterprises, and facilitating the smooth progress of environmental governance. For instance, the public can report environmental violations through environmental protection applications, monitor environmental quality, and offer suggestions for environmental protection, therefore encouraging all sectors of society to participate in environmental protection efforts. Moreover, digital governance improves the efficiency and quality of environmental governance. Through digital technology, environmental data can be automatically collected, analyzed, and processed, significantly reducing manpower and time costs and increasing the efficiency of environmental governance. For example, artificial intelligence and machine learning technologies can quickly process large volumes of environmental data, identify potential environmental risks, and provide scientific recommendations for governance. Digital technology also aids in the informatization and intelligentization of the governance process, enhancing the scientific basis and accuracy of governance decisions and improving the level of environmental governance. For example, intelligent environmental governance systems can simulate the effects of different governance plans, helping decision-makers choose the optimal plan and reducing decision-making errors and resource waste. Furthermore, the widespread adoption and application of digital technology helps raise public awareness of environmental protection. Through digital media and educational platforms, environmental issues and solutions can be more intuitively presented, encouraging participation and support from all sectors of society and advancing the progress of environmental protection. For example, virtual reality technology can allow the public to experience the harm caused by environmental pollution firsthand, therefore strengthening their environmental awareness and proactive behavior. Educational platforms can offer a wealth of environmental knowledge and skills training, helping the public understand and master environmental protection methods and improve their capabilities in this area. In conclusion, the application of digital technology has played an important role in promoting environmental protection and sustainable development at various levels. Industrial digitalization and digital industrialization have improved resource utilization efficiency and production competitiveness. Digital governance has enhanced the efficiency of environmental monitoring and management, and digital media and educational platforms have raised public environmental awareness. These factors provide a solid foundation for achieving green development and building an ecological civilization. In the future, as digital technology continues to advance and proliferate, its role in environmental protection will become even more significant. We should fully utilize digital technology to continuously advance the cause of environmental protection.

5.3. Nonlinear Spillover Effects of the Digital Economy on the Improvement of Ecological Environmental Quality

The relationship between the digital economy and ecological and environmental quality is characterized by nonlinearity rather than simple linearity. To reveal the nonlinear spillover effects between the digital economy and ecological and environmental quality, this study varied the measurement levels of each input variable and observed the corresponding changes in output variables (environmental parameters), ultimately deriving the nonlinear relationship patterns between the digital economy and ecological and environmental quality. The specific steps were as follows: First, the measurement levels of digital industrialization and industrial digitalization increased by 10%, 15%, 20%, and 25% while keeping the measurement levels of other input variables constant. The changes in the measurement levels of environmental pressure and environmental conditions were computed using a neural network model, as depicted in Figure 5. The measurement levels of environmental pressure and environmental conditions initially exhibited significant changes, followed by a gradual slowdown. This is because the development of digital industrialization and industrial digitalization promotes the transformation of production methods and management practices, enhancing resource efficiency. However, with their advancement, the widespread use of electronic products and equipment accompanies substantial energy consumption. Without corresponding advancements in digital governance, this could lead to adverse environmental impacts, diminishing the positive effects of digital industrialization and industrial digitalization on the environment. To analyze the impacts of digital governance and data monetization on the ecological environment, digital governance and data monetization measurement levels increased by 10%, 15%, 20%, and 25% using the same approach while keeping the measurement levels of digital industrialization and industrial digitalization constant. The results indicated in Figure 6 show that increasing the measurement levels of digital governance and data monetization contributes to the enhancement of environmental conditions and governance levels. Digital governance utilizes information technology and data analysis tools to improve governance efficiency and precision, facilitating timely identification and resolution of environmental issues. Through digital monitoring systems, relevant government departments can monitor environmental indicators in real time, identify pollution sources and problem areas promptly, and support environmental governance with data. Additionally, digital decision-making systems can scientifically formulate environmental protection policies and measures, optimize resource allocation, and improve governance effectiveness. Moreover, increasing the measurement level of data monetization implies a more accurate and comprehensive assessment of environmental impact factors. Leveraging digital technology enables detailed collection, analysis, and evaluation of relevant environmental data such as air quality, water quality, and soil pollution, making the impacts of environmental issues and corresponding strategies clearer. However, when the measurement levels of digital governance and data monetization reach a certain threshold, further enhancements in these areas may face diminishing marginal benefits. This means that additional resources and technologies may contribute less to environmental improvement over time. Moreover, with technological and societal advancements, new environmental challenges may emerge, imposing higher requirements and challenges on current levels of digital governance and data monetization. Therefore, as these areas reach certain levels of growth, the effectiveness of environmental governance and environmental condition improvement may gradually diminish.

In summary, the relationship between the digital economy and ecological environmental quality exhibits complex nonlinear effects. While the development of the digital economy contributes to improving environmental quality, it is essential to recognize that once its development reaches a certain level, new challenges may arise. Therefore, there is a need for continuous attention to environmental issues and ongoing enhancement of digital governance and data monetization levels to promote a positive interaction between the digital economy and environmental protection. In summary, the relationship between the digital economy and the ecological environment is complex and nonlinear. Research shows that while digital industrialization and the digitalization of industries initially improve production efficiency and resource utilization, thus positively impacting the environment, the increased use of electronic products and equipment leads to significant energy consumption. If the level of digital governance does not keep pace, the environmental impact may become negative. Although digital governance and data valorization initially enhance environmental governance, their marginal benefits diminish over time. To coordinate the relationship between the digital economy and the environment, it is essential to improve digital governance, promote green technology development, enhance data valorization, strengthen policy guidance and public participation, establish sound regulatory mechanisms, and innovate environmental governance models. Through technological innovation, policy guidance, public participation, and regulatory enhancement, it is possible to achieve a harmonious balance between economic development and environmental protection, therefore advancing green and sustainable development.

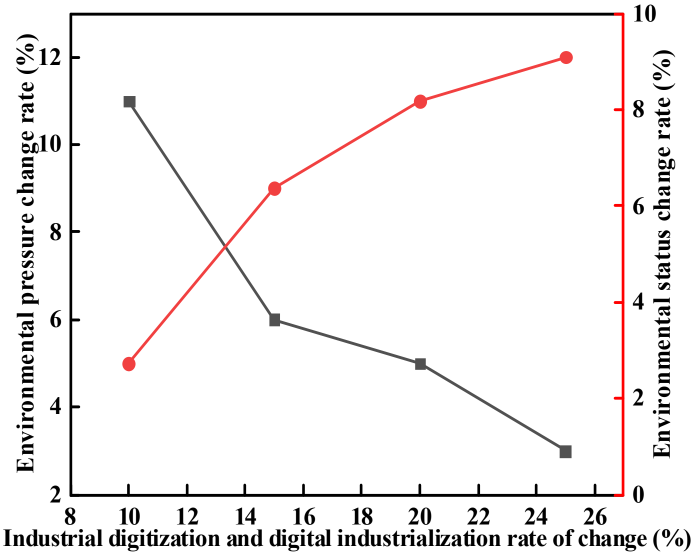


Figure 5. Patterns of changes in environmental pressure and status. The black line corresponds to the left y-axis (Environmental pressure change rate), while the red line corresponds to the right y-axis (Environmental status change rate).

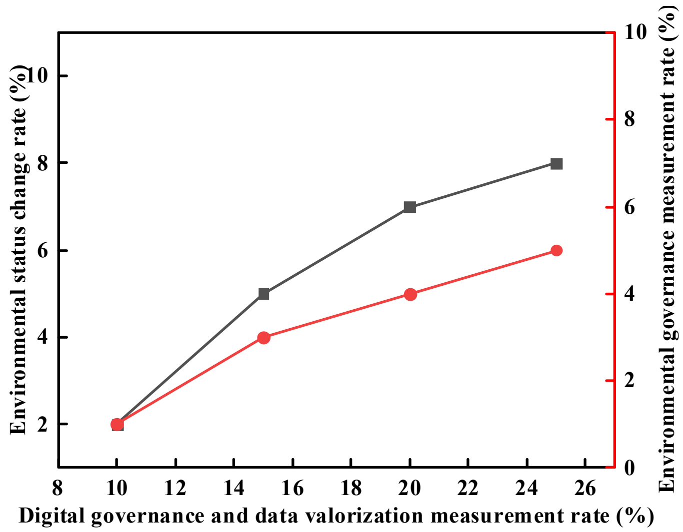


Figure 6. Patterns of changes in environmental status and governance. The black line corresponds to the left y-axis (Environmental status change rate), while the red line corresponds to the right y-axis (Environmental governance measurement rate).

5.4. Analysis of The Mediating Effect of Green Technology Innovation

Green technology innovation not only optimizes production and management methods, improves resource efficiency, and creates new industries and job opportunities but also enhances pollutant treatment efficiency and reduces environmental pollution. The application of these technologies effectively improves air quality, water quality, and soil quality, safeguarding the health and stability of ecosystems. To investigate the impact of green technology innovation on ecological environment protection, this parameter was integrated into the neural network model to reveal the interactive relationships among the digital economy, green technology innovation, and ecological environment. The model's fit relative errors and residual results are shown in Figure 7.

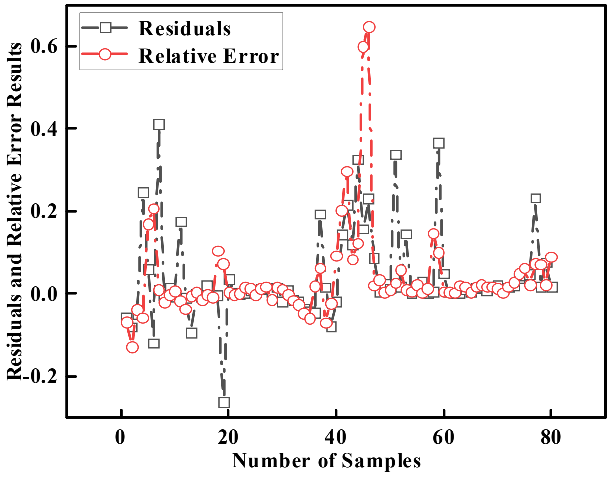
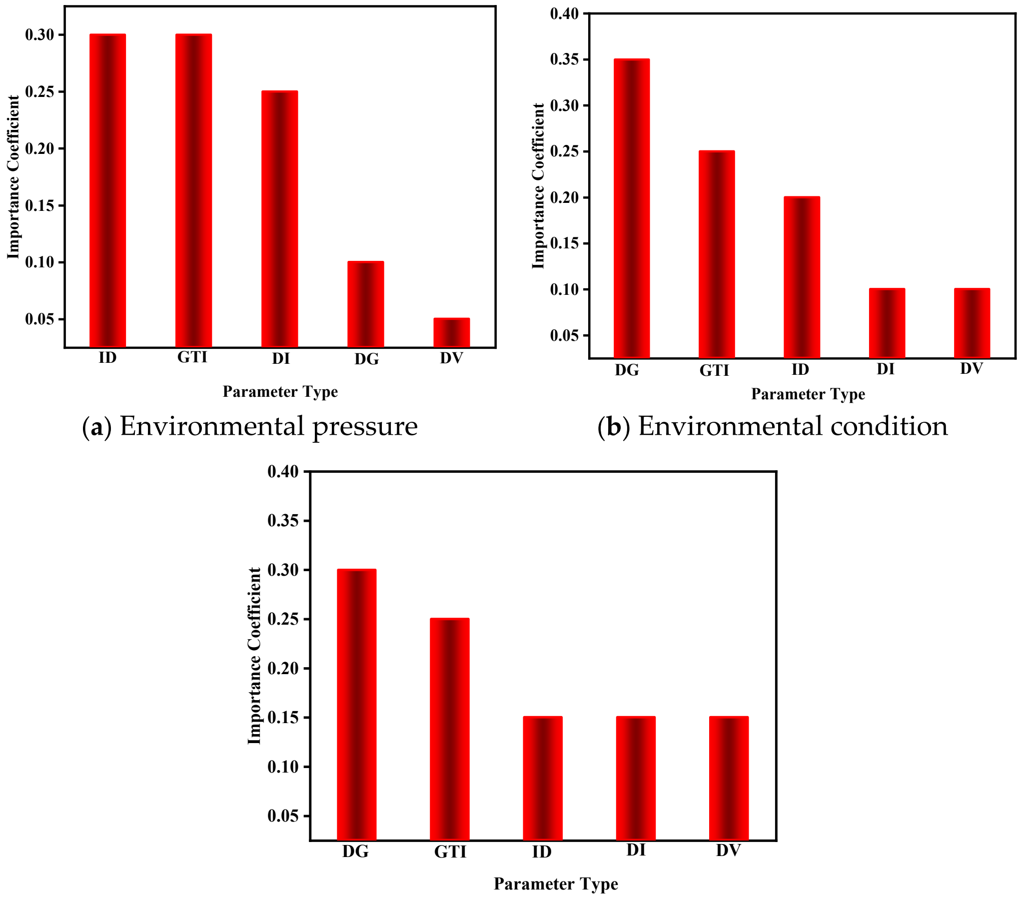


Figure 7. Calculation results of residuals and relative errors.

Figure 7 displays the calculation results of model residuals and relative errors. It is evident that with the inclusion of green technology innovation as an intermediary variable in the model, the model's fitting accuracy is higher, as indicated by smaller residuals and relative errors. This underscores the crucial importance of green technology innovation as an intermediary variable for the development of the ecological environment. To further elucidate the significance of green technology innovation for ecological development, the importance of each parameter was calculated using Equation (10), and the results are shown in Figure 8.

Figure 8 illustrates the impact of green technology innovation on the ecological environment. The results show that green technology innovation plays a pivotal role in improving environmental pressure, environmental status, and environmental governance. Green technology innovation not only brings significant environmental benefits in the short term but also promotes long-term sustainable development of society. In terms of environmental pressure, with the advancement of green technology, the development of clean energy technologies reduces reliance on fossil fuels, decreases greenhouse gas emissions, and mitigates the pace of climate change. For instance, the application of renewable energy technologies such as solar, wind, and hydroelectric power significantly reduces the demand for coal and oil, therefore lowering greenhouse gas emissions. Additionally, the application of high-efficiency energy-saving technologies notably reduces energy consumption, minimizing the exploitation and utilization of natural resources and consequently reducing environmental pressure. For example, using smart-grid technology and efficient lighting devices can help achieve energy optimization and reduce energy waste. From the perspective of enhancing environmental governance, green technology innovation provides more tools and methods for environmental management. The application of technologies such as digital monitoring systems and intelligent environmental protection equipment enables real-time monitoring and management of environmental pollutants, therefore enhancing the efficiency and accuracy of environmental governance. For example, the utilization of Internet of Things (IoT) technology enables real-time monitoring of air quality, water quality, and soil pollution, facilitating prompt identification of environmental issues and effective remedial measures. Furthermore, green technology innovation also promotes the formulation and implementation of environmental protection policies and regulations, therefore advancing the level of environmental governance. For instance, through big data analysis, the effectiveness of different environmental governance measures can be evaluated, optimizing the formulation of environmental policies and enhancing governance effectiveness. In terms of improving environmental status, green technology innovation promotes efficient and circular utilization of resources, reducing resource consumption and waste, therefore directly improving environmental quality and enhancing environmental status. For example, the promotion of circular economy models through resource recycling and waste regeneration significantly reduces reliance on primary resources and reduces waste emissions and environmental pollution. Additionally, the development of green agricultural technologies, such as organic and ecological farming, reduces the use of fertilizers and pesticides, protects soil and water sources, and improves the sustainability of agriculture.



(**a**) Environmental pressure (**b**) Environmental condition

(**c**) Environmental governance

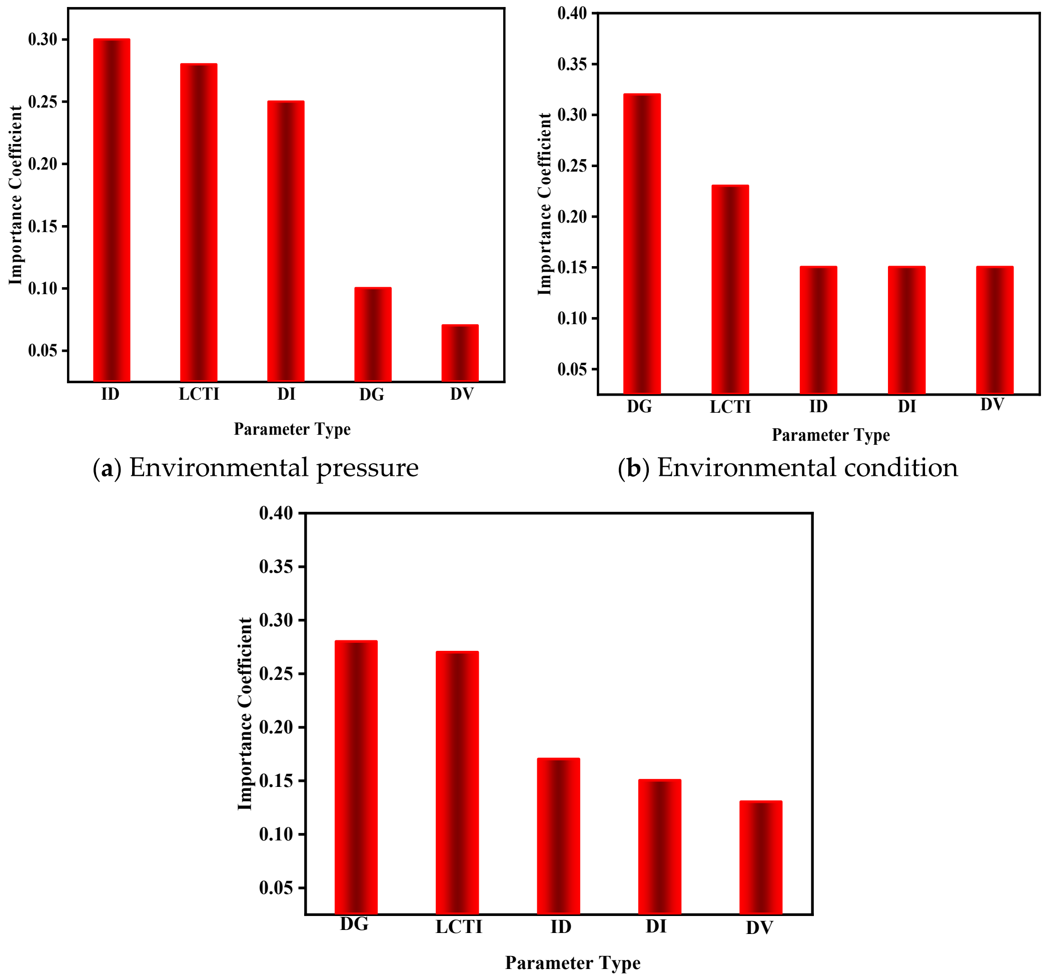
Figure 8. Analysis results of parameter importance. Notes: GTI means green technology innovation.

Overall, the improvement brought about by green technology innovation in environmental pressure, environmental governance, and environmental status is multifaceted and comprehensive. Through the research and application of innovative technologies, effective control and management of environmental issues can be achieved, laying a solid foundation for achieving sustainable development goals. For instance, the promotion of green building technologies using energy-saving building materials and intelligent management systems can reduce building energy consumption and carbon emissions, improving urban environmental quality. Therefore, green technology innovation is regarded as one of the key approaches to addressing contemporary environmental issues, deserving attention and support from governments, businesses, and society at large. To further promote green technology innovation, various measures should be taken. First, governments should increase funding for green technology research and development, provide policy support, and encourage enterprises and research institutions to engage in the research and application of green technologies. Second, enterprises should actively assume social responsibilities, invest resources in the innovation and application of green technologies, and promote the implementation of green production and operation modes. Additionally, the public should enhance environmental awareness, actively support and participate in the promotion and application of green technologies, and collectively promote sustainable social development.

In conclusion, green technology innovation plays a crucial role in environmental protection and sustainable development. Through the concerted efforts of governments, enterprises, and the public, the goals of green development can be achieved, leading to the construction of a more beautiful ecological civilization.

5.5. Robustness Test

The indicator of low-carbon technology innovation focuses on technological innovations aimed at reducing carbon emissions and greenhouse gas emissions, which are closely related to green technology innovation. To ensure the reliability of the empirical results mentioned above, this section conducts robustness tests by replacing core variables. Based on the weight analysis results between the layers of the neural network model, combined with Equation (10), the importance of each parameter is calculated, and the results are shown in Figure 9.



(**a**) Environmental pressure (**b**) Environmental condition

(**c**) Environmental governance

Figure 9. Analysis results of parameter importance. Notes: LCTI means low-carbon technology innovation.

As shown in Figure 9, it can be observed that the order of importance of various input parameters on the output parameters did not change significantly. Industrial digitalization and digital industrialization have a substantial impact on environmental pressure, while digital governance and data valorization have a relatively smaller effect. Regarding environmental status and governance, digital governance has a notable influence. Furthermore, the calculation results after replacing core variables also reaffirmed the critical role of low-carbon technology innovation in improving ecological environmental quality.

Low-carbon technology innovation contributes significantly to enhancing the environment by reducing resource consumption, mitigating environmental pollution, cutting greenhouse gas emissions, and improving resource efficiency. It effectively reduces carbon emissions from industrial production and energy use, therefore slowing global climate change and preserving ecosystem integrity and stability. Moreover, low-carbon technology innovation plays a promoting role in the high-quality development of the digital economy and sustainable development of the environment. By integrating environmental protection, energy conservation, and clean production concepts and technologies, low-carbon technology innovation underpins the sustainable development of the digital economy, achieving a beneficial coexistence of economic growth and environmental protection. This positive cycle promotes green economic transformation, establishing a solid foundation for the continuous development of society in the future.

In summary, this study demonstrates the feasibility of revealing the interaction patterns among the digital economy, green technology innovation, and ecological environmental quality by constructing a neural network model. The computational results of the model are reliable, providing a new perspective for further promoting the coordinated development of the economy and the environment.

6. Conclusions and Recommendations

This paper conducted statistical analyses on the levels of digital economy, green technology innovation, and ecological environment quality measurements across 285 prefecture-level cities in China in recent years. The study analyzed the correlations among these factors and employed a neural network model to reveal their interactive relationships, aiming to provide insights for the coordinated development of the digital economy and ecological environment.

Through assessing the current status of the Chinese digital economy, green technology innovation, and ecological environment quality in recent years, it has been observed that environmental pressure significantly affects ecological environment quality, with notable differences among different regions. Relatively developed areas like Shanghai and Shenzhen exhibit lower environmental pressure due to the development of high-tech and green industries, whereas regions dependent on energy and traditional processing and manufacturing industries, such as Shanxi, Jilin, and Hebei, face higher environmental pressure. Additionally, industrial digitalization serves as a core driving force of the digital economy, playing a decisive role in enhancing production efficiency and fostering innovation in new industry forms and business models. Meanwhile, green technology innovation is crucial for promoting environmental protection and sustainable development, but there remains substantial room for improvement in its application and innovation nationwide, especially in central and western cities.

By constructing a neural network model and combining weight analysis, the direct effects of the digital economy on the improvement of ecological environment quality were analyzed. The results indicate that for environmental pressure, industrial digitization and digital industrialization have the most significant impact, with importance coefficients of 0.45 and 0.3, respectively, while data valorization has the least impact. For environmental status and environmental governance, digital governance has the most significant impact.

The relationship between the digital economy and ecological environment quality exhibits complex nonlinear effects. As the levels of digital industrialization and industrial digitization continue to increase, their promoting effects on environmental quality gradually strengthen. However, when the level of digital governance does not keep up, it may bring certain negative impacts on the ecological environment, reducing the positive effects of both on the environment. Furthermore, the improvement of digital governance and data valorization levels significantly contributes to the improvement of environmental status and the enhancement of environmental governance. However, when the levels of digital governance and data valorization reach a certain level, further enhancement of digital governance may encounter diminishing marginal benefits.

Using green innovation technology as a mediating variable, weight analysis results reveal that green technology innovation has a significant impact on environmental pressure, environmental status, and environmental governance. With the continuous advancement of green technology, the promotion and application of clean energy technologies reduce dependence on fossil fuels and alleviate environmental pressure. Green technology innovation expands tools and strategies for monitoring the environment, enhances environmental governance levels, and positively affects improving environmental status. Based on the above research conclusions, this paper provides the following suggestions and insights.

China's strategy to promote the development of the digital economy is highly consistent with and complementary to its goal of improving environmental quality through green technology innovation. Both rely on technology-driven innovation and receive policy support, creating a win–win effect. The digital economy enhances efficiency and productivity through information technology, while green technology achieves sustainable development through environmental innovation. Despite different core goals and implementation paths, the two are compatible in policy. The digital economy provides tools and platforms for green technology, while green technology creates application scenarios and market demand for the digital economy, driving both economic growth and environmental protection. Given the regional differences in the development of the digital economy and environmental quality across China, as well as the multiple challenges posed by the digital economy, green technology innovation, and environmental quality, regions should strengthen cooperation and exchange to explore solutions together. The developed eastern regions can share their successful experiences in digital transformation, provide technical support, and offer talent training to promote digital transformation in the central and western regions. Meanwhile, the central and western regions should leverage their resource advantages to collaborate with the developed regions on green technology innovation projects, accelerating environmental protection and high-quality economic development. Through regional cooperation and exchange, these challenges can be jointly addressed, achieving mutual benefits and win–win outcomes. Based on the results of the neural network model and weight analysis, it is recommended that industrial digitization and digital industrialization be focused on and that digital governance be enhanced in the process of digital economy development. This implies strengthening the application of digital technology in industrial production and economic operations, optimizing industrial structure, improving resource utilization efficiency, and reducing environmental pressure. Simultaneously, efforts should be made to enhance the construction of digital governance systems, achieve real-time monitoring of environmental issues, and precise governance, promoting continuous improvement in environmental status and environmental governance levels.

Considering the complex nonlinear relationship between the digital economy and ecological environment quality, it is recommended that the advancement of digital governance levels be synchronized during the promotion of digital industrialization and industrial digitization. This includes establishing more intelligent and refined digital environmental monitoring systems and enhancing the capabilities of digital environmental governance and decision-making. Additionally, attention should be paid to the potential diminishing marginal benefits when digital governance and data valorization levels reach a certain stage, adjusting policy measures promptly to avoid excessive reliance on digital means and neglecting substantive environmental protection and governance.

Furthermore, public awareness and education play a crucial role in cultivating environmental awareness within China's digital economy ecosystem. By raising public awareness and knowledge of environmental protection, consumer behavior can be influenced to increase demand for eco-friendly products and services, prompting companies to enhance environmental standards and innovate green technologies. Enhanced public environmental awareness can also exert public pressure, encouraging companies to fulfill their environmental responsibilities and driving green consumption through market forces. Additionally, public participation and oversight can encourage the government to formulate and implement stricter environmental regulations and standards. To achieve favorable ecological outcomes, it is necessary to strengthen environmental education by incorporating environmental protection into all levels of the education system and enhancing public awareness through media campaigns and public activities. Simultaneously, increasing public participation through organizing environmental activities and volunteer programs can promote green consumption. This can be furthered by implementing green labeling certification and incentive mechanisms to guide consumers toward eco-friendly products and services. Utilizing digital platforms to disseminate environmental knowledge and skills and enhancing the transparency of environmental data will further empower the public to supervise the environmental actions of companies and the government, thus promoting sustainable development across society.

Based on the significant impact of green technology innovation on environmental pressure, environmental conditions, and environmental governance, it is recommended that cooperation between the government, enterprises, and research institutions be strengthened to promote the continuous advancement and application of green technology innovation. First, the government can propose corresponding policy guidance and incentive measures, such as tax incentives, financial subsidies, and green credit policies, to encourage enterprises to invest in green technology and sustainable projects and ensure that enterprises consider environmental protection during digital transformation. Second, formulating regulations and standards is crucial. By establishing strict environmental protection regulations and digital economy-related environmental standards, the government can compel enterprises to comply with emission limits, waste disposal norms, and other environmental standards, ensuring that they fulfill their environmental responsibilities while pursuing economic benefits. Thirdly, enhancing environmental supervision is essential. Developing a sound supervision mechanism, conducting regular inspections of enterprises' environmental protection measures, and imposing severe penalties on those violating environmental regulations will ensure that enterprises voluntarily comply with environmental laws and fulfill their social responsibilities. Lastly, increasing funding and developing policies to incentivize green technology innovation is vital. This includes encouraging enterprises to increase R&D investment accelerating the development and application of green technologies. Additionally, promoting the establishment of cross-departmental and cross-industry green technology innovation alliances can drive the widespread application of green technology in various fields, achieving a win–win situation for environmental protection and high-quality economic development.

In addition, in future research, efforts should be made to expand the model's database as much as possible, considering more factors, such as the regulatory effects of government on the three elements. Further investigation into how the development of the digital economy affects ecological environment quality and exploring the potential of the digital economy in improving environmental benefits should also be undertaken. Moreover, exploring how to integrate green technology innovation with the development of the digital economy to promote the sustainable development of the digital economy and enhance ecological environment quality is essential. This includes the application, innovation, and promotion of green technology in digital industries, as well as the support of policy and market mechanisms. A thorough analysis of the relationship between the development of the digital economy, green technology innovation, and ecological environment quality in different regions should also be conducted, and differentiated policy recommendations and development paths should be proposed based on the characteristics of different regions.

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