Int J Environ Res (2024) 18:99
https://doi.org/10.1007/s41742-024-00651-0

RESEARCH PAPER

The Impact Mechanism and Effect Evaluation of Digital Economy Development on Regional Carbon Emission Reduction: Evidence from Provincial Panel Data in China

Chuang Li[1] · Qin Zhao[2] · Liping Wang[3]

Received: 27 September 2023 / Revised: 26 July 2024 / Accepted: 31 July 2024

Abstract

In the era of digitalization and under the context of "dual carbon", The green attributes of the digital economy have attracted attention, and it is worth exploring whether it can reduce carbon emissions. This paper uses inter-provincial data from 2011 to 2021 to examine whether the digital economy will play a positive role in carbon reduction. The findings are as follows: (1) There is a significant negative effect of digital economy development level on carbon emission intensity. (2) In the mediation test section, it is verified that the digital economy can reduce carbon emission intensity by optimizing the industrial structure, promoting the transformation of the energy consumption structure, improving green technology innovation, and optimizing the allocation of resources. (3) The article includes government intervention and human capital as moderating variables, and the results show that Human capital has a positive moderating effect between digital economy and carbon emission intensity, while government intervention has a negative moderating effect. (4) Digital economy has threshold effect on carbon emission intensity. (5) The influence of digital economy on carbon emission intensity shows a heterogeneous relationship between regions and factor endowments. The carbon emission reduction of digital economy in western and northeastern regions is more significant, and the abundance or scarcity of capital, labor and technology factors have different impacts on the carbon emission reduction effect of digital economy. At the same time, it further analyzes the influence of the difference of local government behavior. This paper argues that provinces and cities should strengthen the construction of digital economy, and at the same time should promote the coordinated development of digital economy among regions, which is important to achieve carbon emission reduction.

Article Highlights

- **The impact of the lnDE on lnCEI in 30 provinces and cities from 2011–2021 was studied.**
- **The mediating, threshold, and moderating effects were investigated.**
- **The lnDE can significantly reduce the lnCEI.**
- **Gov and lnHumc can positively moderate the impact of on lnCEI.**

✉ Liping Wang
lindsey18@jmu.edu.cn

Chuang Li
lichuang@jmu.edu.cn

Qin Zhao
zq360a@163.com

1 School of Business Administration, Jimei University, Xiamen 361021, China

2 School of Business Administration, Henan Polytechnic University, Jiaozuo 454000, China

3 Finance and Economics College, Jimei University, Xiamen 361021, China

Published online: 20 August 2024

Keywords Digital economy · Carbon emission intensity · Spatial Durbin model · Mediating effect · Threshold effect

Introduction

The climate issue is now one of the serious challenges facing the global community. According to the International Energy Agency (IEA), global CO_2 emissions fell by about 2 billion tons in 2020 as a result of the impact of COVID-19, making the largest absolute drop in history. But China was the only major economy to achieve an increase in carbon emissions, i.e., China's annual carbon emissions increased by 0.8% in 2020 compared to 2019. The following year, the International Energy Agency (IEA) released a report that mentioned a surge in global CO_2 emissions of about 1.5 billion tons in 2021, due to the recovery in economic activity. This marks the second-largest increase in history, and reverses the significant decline in 2020 caused by the COVID-19. To mitigate the adverse effects of the excessive increase in carbon emissions, countries are beginning to take practical action to meet their carbon reduction targets, such as the EU's push for a "green deal" and a sustainable recovery plan, the U.S. rejoining the Paris Agreement and putting climate issues at the heart of policy development, and China has also set a "double carbon" target. According to the comparison chart between China's total carbon emissions and the world's total carbon emissions (Fig. 1). From the figure, we can see that China's total carbon emissions account for about one-third of the world's total carbon emissions, and are higher than the total carbon emissions of the US, which indicates that China's role in global climate governance should not be underestimated. However, at present, in the global scope, the countries that achieve the peak of carbon emissions are basically developed countries or post-industrial countries, but China and European and American countries are at different levels of development and economic growth stages, with different types of industrial structure, energy consumption intensity and energy consumption structure, and China's total carbon emissions are significantly more than Europe and the United States. Therefore, the successful experience of low-carbon transformation in foreign countries cannot be replicated in China, and China needs to find a low-carbon transformation path suitable for national conditions to meet the needs of carbon dioxide emission reduction. In conclusion, reducing carbon dioxide emissions is an important task for global environmental protection, and actively exploring the drivers and paths of carbon emission reduction has become a top priority for countries around the world.

Following the three technological revolutions, global technological innovation has entered an unprecedented period of intensive activity, and the digital economy is leading a new wave of technological innovation and industrial change. In the 13th Five-Year Plan period, China has carried out the development strategy of digital economy, made digital economy one of the main directions of development, and continued to enrich and improve the

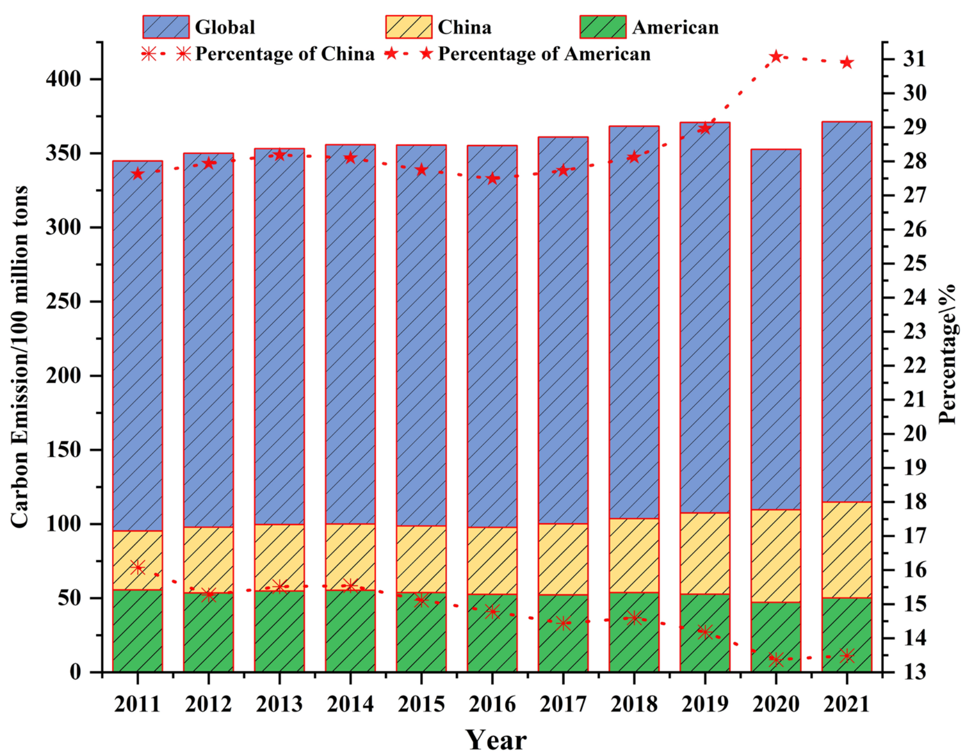

Fig. 1 China's position in global carbon emissions

construction of digital infrastructure. During the 14th Five-Year Plan period, China proposed to develop digital economy and build digital China, which is the key path to achieve high-quality development and build a new development pattern. The "14th Five-Year Plan" for the development of the digital economy further clarifies the guiding ideology, basic principles, development goals, key tasks, and guarantee measures to promoting the effective development of the digital economy during the 14th Five-Year Plan period. A series of planning documents on the development of the digital economy has pushed the scale of China's digital economy to increase rapidly. According to the "White Paper on Digital Economy Development (2022)" published by the China Academy of Information and Communication Technology, China's digital economy reached 45.5 trillion yuan in 2021, more than double the size of the "13th Five-Year Plan" and accounting for 39.8% of GDP. Given the key role of the digital economy in driving China's economic growth, it is particularly important to examine whether the digital economy is also important for achieving the goal of carbon neutrality.

In the era of digital economy, data has become a key production factor in economic activities and an important support for building a new development pattern, which can fundamentally change the traditional economic activity model and develop new industries and development models (Shi 2022). On the one hand, the digital economy itself has green attributes, and the high permeability of digital elements accelerates the integration of digital industries with traditional industries, which can promote the upgrading of industrial structures in traditional industries (Hao et al. 2023), optimize resource allocation and save production resources (Wang et al. 2024a), etc. Europe is promoting the transformation of digital industries by adopting Industry 4.0 technologies to improve production efficiency, resource utilization efficiency and reduce carbon emissions. Century-old industrial giant Siemens is known as the representative enterprise of German Industry 4.0. Siemens was one of the earliest industrial companies to set a carbon neutral target for its operations by 2030, having set a carbon neutral target before the Paris Agreement. Today, Siemens is expanding its digital capabilities to the field of talkative, its digital technology can help enterprises, production lines to understand the production and operation data, with the help of carbon inventory, carbon reduction knowledge, the digital twin capabilities gradually extended to carbon twins, not only to achieve their own carbon reduction, but also to put forward requirements for suppliers, to help downstream enterprises to reduce carbon. In addition to making its own operations carbon neutral by 2030, Siemens aims to reduce the carbon footprint of its supply chain by 20% by 2030 and be carbon neutral across the board by 2050. At the same time, the development of the digital economy provides conditions for green technological innovation, which can accelerate the production of clean energy and promote the transformation of the energy consumption structure (Shahbaz et al. 2022), thus reducing the level of carbon emissions. On the other hand, the digital economy has a "green paradox" effect, as the digital economy industry is a high-energy-consuming industry, and the construction and operation of digital centers will consume a large amount of energy, and the rapid expansion of its scale will result in the rapid growth of carbon emissions in the process of developing the digital economy. With the above analysis, it is crucial to study the impact of the development of digital economy on carbon emission reduction to achieve the goal of carbon peaking and carbon neutrality. Then, this paper considers how the digital economy affects the level of carbon emissions? What is the transmission mechanism by which the digital economy has an impact on carbon emission levels? Due to the differentiation of regional development in China, is there regional and factor endowment heterogeneity in the impact of digital economy on carbon emissions? Based on this, this paper uses the spatial Durbin model to explore the impact of digital economy on carbon emission intensity in 30 provinces of China from 2011 to 2021, and also studies the impact of digital economy on carbon emission intensity by dividing provinces into four regions: eastern, central, western, and northeastern, and explores the heterogeneity of digital economy on carbon emission intensity according to different factor endowment capabilities. In the part of exploring the transmission mechanism of digital economy on carbon emission intensity, this paper uses the mediating effect model based on the spatial Durbin model to analyze.

The possible marginal contributions of this paper are as follows: (1) Considering the spatial relevance of carbon emission intensity, the article introduces a spatial econometric model to explore the spatial influence effect of digital economy on carbon emission intensity, which complements the results of existing studies at the spatial level. (2) In terms of the selection of research variables. The article analyzes the process of transmission mechanism of digital economy on carbon emission intensity, considering that data has strong mobility and can overcome the hindrance of information in the process of flow (such as information asymmetry and geopolitical hindrance, etc.), so that resource allocation can be optimized. And existing studies lack resource allocation as an intermediate path to explore the impact of digital economy on carbon emission intensity. Therefore, this paper measures the capital mismatch index and labor mismatch index to characterize the degree of resource mismatch and verify the mediating role of resource mismatch in the process of digital economy affecting carbon emission intensity. (3) Considering that government intervention and human capital may have a regulating effect between digital economy and carbon emission intensity, this paper introduces two variables, government intervention and human capital, to further explore the regulating effect between digital economy and carbon emission intensity.

The rest of the paper is organized as follows: firstly, in the second part, the literature in related fields is collected and analyzed, and the literature review is summarized to obtain a literature review. The theoretical analysis and research hypothesis of the impact of digital economy on carbon emissions are given in the third part. The fourth part designs the variables, data and methods used in this study, and briefly describes the spatial and temporal distribution characteristics of carbon emission intensity and digital economy development level in each province. The empirical results and discussion of this paper are given in the fifth section. Figure 2 presents the research framework of this study.

Literature Review

Overview of the Benefits of the Digital Economy

The term "digital economy" was first mentioned in "The Digital Economy: Promise and Peril in the Age of Network Intelligence" by Tapscott, but it did not define the concept of digital economy. Since the 21st century, digital technologies such as cloud computing, big data, blockchain and artificial intelligence have developed rapidly, and human society has entered the era of digital economy. More and more scholars have started to pay attention to the benefits brought by digital economy to human society, and related theoretical research has continued to be in-depth, and the concept of digital economy has become clear. However, since the digital economy is dynamic rather than static, there is no unified opinion on the concept of digital economy, for example, the definition of digital economy in the "14th Five-Year Plan for Digital Economy Development" is the main economic form after agricultural economy and industrial economy, which is based on data resources as the key element. The digital economy is an economic model in which information technology and digital technology are the main factors of production, while the traditional economy is an economic model in which material production and exchange are the main forms of production. In comparison, the digital economy has advantages over the traditional economy, such as high production efficiency, high innovation capacity, and high resource utilization. Specifically, the advantages arising from the digital economy can be divided into the following aspects: (1) In terms of social benefits. The digital economy can significantly contribute to economic growth (Ozturk and Ullah 2022), and Lyu et al.(2023) concluded that the digital economy has significant positive effects on green total factor productivity as well as spatial spillover effects with U-shaped characteristics, while the heterogeneity study

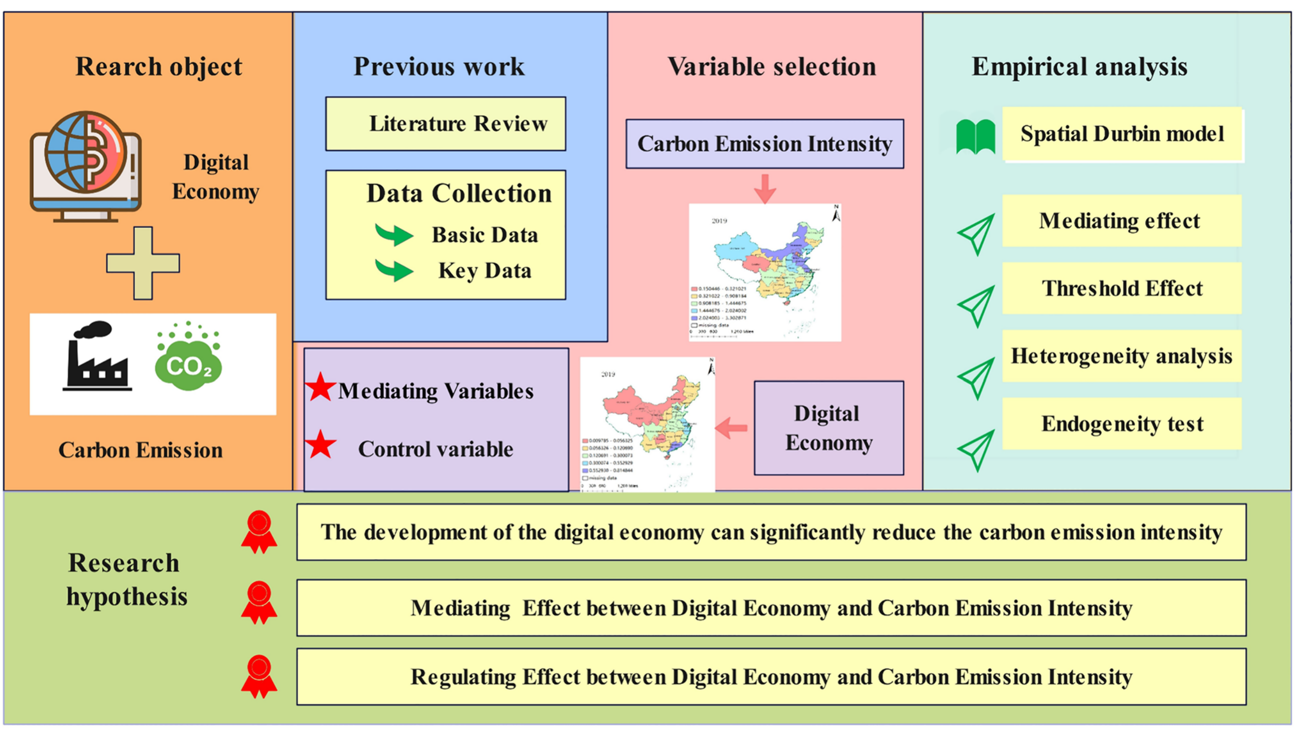

Fig. 2 Research framework

results indicate that a "digital divide" does exist in China The results of the heterogeneity study also suggest that there is a "digital divide" in China, and that central cities can get greater green economic growth from the development of the digital economy in China, which in turn can indicate that the digital economy can accelerate the structural transformation of the economy (Pan et al. 2022). (2) At the level of business efficiency. The digital economy enhances business activities and improves firm performance by reducing transaction costs and optimizing resource allocation (Huo and Wang 2022), which can improve the competitiveness of firms (Skare et al. 2023). (3) At the industry level. The digital economy and AI promotes advanced industrial structure by driving consumer demand, and can empower technological innovation to promote rationalization of industrial structure (Wang et al. 2023b). At the same time, the development of digital economy brings new factors of production and promotes the emergence of new industries, as well as the integration of new generation of information technology with various industries to form new industrial models (Su et al. 2021). (4) At the energy level. The digital economy can promote the transformation of the energy structure as well as improve the efficiency of energy use. For example, Chen (2022) confirms that the digital economy drives the development of clean energy through innovation and bank loans, and that the impact of the digital economy varies at different regional scales, and also confirms that the digital economy has positive spatial effects and can drive the development of clean energy in local and neighboring cities. The analysis of energy transition from the production side as well as the consumption side shows that the digital economy can significantly contribute to the energy transition and has a higher contribution to renewable energy production than renewable energy consumption. (5) At the technological level. The digital economy can improve green technology innovation through multiple means. For example, the use of digital financial instruments can improve green technology innovation by alleviating financing constraints (Lin and Ma 2022). In general, the digital economy can generate more positive externalities compared to the traditional economy. Nowadays, with the continuous development of digital economy, it will become the main direction of future economic development.

A Review of the Relationship between the Digital Economy and Carbon Emissions

Carbon emissions are the emissions of greenhouse gases such as carbon dioxide produced by human activities, including transportation, agriculture, and industrial activities. In recent years, as industrialization and urbanization have been accelerating, carbon emissions have been increasing along with them. The large increase in carbon emissions can lead to problems such as climate warming and ecosystem collapse, which have caused concern in many countries and regions. To cope with this problem, countries have also developed policies and measures to reduce carbon emissions, such as carbon trading (Goulder et al. 2022), carbon tax (Zhao and Mattauch 2022), carbon pricing (Abrell et al. 2022), environmental tax (Fang et al. 2022), and policy coordination to reduce emissions (Li et al. 2023a). By implementing the above carbon reduction policies, quantitative constraints and limits on carbon emissions can be imposed to promote individuals and enterprises to shift to a low-carbon economic model. Estimation and projection of carbon emissions from different industries and activities can predict carbon emission trends and can provide reference for setting carbon reduction targets. Considering the differences in resource endowments and economic development levels of different regions, the spatial distribution characteristics of carbon emissions have attracted the attention of scholars, Tang et al. (2024) verified that carbon emissions in Chinese provinces have obvious spatial dependence and spatial agglomeration, and Zhou et al. (2023) analyzed the spatial and temporal patterns and evolutionary characteristics of carbon emissions to obtain that carbon emissions in the east is significantly higher than that of the central and western regions. At present, academics have revealed that the influencing factors regarding carbon emissions are mainly focused on the following aspects: industrial structure, energy structure, energy intensity, economic development level, population size, environmental regulation, green technology innovation, foreign direct investment, etc. (Zhong and Liu 2022; Liao 2023; Guo et al. 2024; Li et al. 2023b; Hong et al. 2022; Zhang et al. 2022). With the introduction of the "double carbon" target, many studies have been conducted to explore ways to reduce carbon emissions, such as researching and developing feasible carbon reduction technologies and establishing carbon markets and policies. The transformation of energy mix can have a negative effect on carbon emission reduction, and improving energy efficiency can also reduce carbon emissions (Li et al. 2022c). In terms of technology application, carbon capture, storage and utilization (CCUS) become a key tool for climate change mitigation (Gowd et al. 2023). In terms of environmental policies, Li et al. (2022a) explored the effect of environmental regulations on the carbon intensity of tourism with the help of panel regression model and panel threshold model, and the results showed that there is a significant "backward reduction" effect of environmental regulations on the carbon intensity of tourism.

The above-mentioned studies on the influencing factors and emission reduction paths of carbon emissions, scholars expect to promote the process of global carbon emission reduction and mitigate the adverse effects of climate change on human society and the environment. As the scale of the digital economy continues to expand, Countries around the world, including China, have been actively implementing smart city pilots. Over the years, the EU has been committed to building a sound digital economy governance framework in line with the development of the digital age around the three core areas of data governance, platform governance and artificial intelligence technology governance, which has become an important model for global digital economy governance. At the same time, European cities are also actively exploring the application of digital technology to build a green, livable, smart digital city, including London, Amsterdam, Vienna, Paris and Hamburg are typical. According to the DCI index, the top digital performers are Copenhagen, Amsterdam, Beijing, London and Seoul. The world is very concerned about the digital economy, combined with the current hot issues of carbon emission reduction, the environmental impact of the digital economy, especially carbon emissions, has attracted attention from all walks of life. Compared with traditional industries, the digital economy has been given a "green halo" effect, and it is widely believed that the development of the digital economy should improve environmental performance. Therefore, under the goal of "double carbon", scholars have tried to integrate the digital economy into the carbon reduction pathway and study the impact of the digital economy on carbon emissions. However, there is no consensus on the effect of the digital economy on carbon emissions. The existing studies on the effect of digital economy on carbon emissions can be divided into "positive externality" effect, "negative externality" effect, and the non-linear relationship between digital economy and carbon emission reduction. The "positive externality" mainly reflects that the digital economy can reduce carbon emissions by improving energy structure, optimizing industrial structure, and promoting green technology innovation (Zhang et al. 2022b; Wang et al. 2022b). The "negative externality" is mainly reflected in the fact that China's digital economy mainly adopts the development method of rough outward expansion, and the rapid expansion of the scale of the digital economy has led to the rapid growth of carbon emissions from the digital economy, and data centers and communication networks are the main sources of carbon emissions from new infrastructure, and gradually become one of the main sources of carbon emissions (Qu et al. 2022). This "negative externality" effect is also recognized by Zhang et al. (2022c), who argue that the development of China's digital economy exacerbates carbon emissions because improving energy efficiency can reduce carbon emission levels, but the development of the digital economy is not conducive to improving energy efficiency, which indirectly increases carbon emissions. On the other hand, Ahmadova et al. (2022) argue that the digital economy can bring benefits to environmental performance, but that an excessive digital economy can produce a "rebound effect" by increasing energy consumption, leading to increased environmental pollution. This view is also supported by Wang et al. (2024b), who believes that under the influence of financial development and trade opening, the impact of ICT on carbon dioxide shows a "U" shape. In order to more specifically analyze the impact of digital economy on carbon emission reduction, this paper also explores from the perspective of industry and regional level. It has been studied from the perspectives of logistics, construction, industry and manufacturing (Yang and Zhong 2023; Wang et al. 2023c; Wu and Deng 2023; Teng and Zheng 2023), and most relevant studies have proved that digital economy can achieve carbon emission reduction, and they are mainly achieved through industrial structure upgrading and technological innovation. From the perspective of different regions, few foreign literatures directly study the impact of digital economy on carbon emissions, and generally study the environmental benefits generated by digital-related technologies. Azam et al. (2021) verified 10 major carbon dioxide emitting countries and proved that ICT can promote economic growth, while the environmental results produced showed that ICT is conducive to reducing carbon dioxide emissions. Ahmed et al. (2016) argues that ICTs can make systems smarter in various ways and can make systems more environmentally friendly by utilizing renewable energy sources. Villanthenkodatha et al. (2022), taking South Africa as an example, verified that information and communication technologies (ICTs), as measured by mobile phones, energy consumption and economic growth, can significantly increase the level of environmental degradation. But information and communication technologies, as measured by Internet access and financial development, can help reduce CO_2 emissions. Of course, not all scholars' research shows that ICT is beneficial to CO_2 emissions. For example, Amri et al. (2019) took Tunisia as a study example, and the results showed that ICT did not reduce CO_2 emissions in the country.

Summarizing the existing related literature, scholars have studied the influencing factors of carbon emissions and the paths of emission reduction from various perspectives, but due to the significant spatial correlation of carbon emission intensity among regions, and the existing studies involving the analysis of the spatial effects of the digital economy on carbon emissions are relatively lacking. At the same time, the development of digitalization has an obvious role in improving the flow and dissemination of information and promoting the effective allocation of resources, while the existing literature rarely considers the path that the digital economy can reduce the level of carbon emissions by improving the efficiency of resource allocation. Therefore, this paper investigates the spatial effect of the digital economy on carbon emissions by invoking the spatial Durbin model, and introduces the resource mismatch index and labor mismatch index to characterize the degree of resource mismatch, and investigates whether the digital economy affects carbon emissions intensity by improving resource allocation efficiency, which further complements the study of the intrinsic mechanism of the digital economy on carbon emissions intensity.

Theoretical Analysis and Research Hypothesis

Direct Impact of Digital Economy on Carbon Emission Intensity

In recent years, due to the rapid development of digital technology, China's "Internet + " model has also entered a white-hot stage. At the micro level, the development of the Internet provides enterprises with technical means and management tools, etc., which can improve the R&D design and management methods of enterprises, and greatly improve their energy utilization technology and production technology, thus improving their energy efficiency as well as reducing energy consumption (Ren et al. 2021). At the same time, the advantages of digitalization are more prominent in times of COVID-19, such as online education and online offices, suggesting that the digital economy can reduce energy consumption by changing the lifestyles of residents, thus reducing environmental stress (Zhang et al. 2022a). At the macro level, the development of the digital economy is based on technologies such as the Internet and big data, which have rich data elements. The data elements have strong mobility, which can reduce the communication barriers and information asymmetry among various links of social and economic operation, reduce ineffective economic activities and resource consumption in the development process, promote the flow and dissemination of various elements, and improve the coordination and innovation capacity among regions or enterprises (Zhu et al. 2022), and realize the effective allocation of resources, which in turn can reduce factor losses. Furthermore, the digital industry itself has green attributes, and the development of digitalization can promote the combination of digital industry and traditional industry, and help enterprises transform toward digitalization, intelligence and greening, which can achieve the purpose of reducing carbon emissions (Ge et al. 2022). Based on this, the hypothesis is proposed that:

Hypothesis 1 The development of the digital economy can significantly reduce the carbon emission intensity.

Intermediary Effect Between Digital Economy and Carbon Emission Intensity

1) Industry Structure. Some scholars have argued that with the rapid development of digital economy, Internet industry, e-commerce industry and communication industry can crowd out high energy-consuming industries, and the virtual nature, high permeability, value-addedness and externality of the digital economy provide intelligent, networked and digital technological support for green transformation (Yi et al. 2022), which can promote the development of a green and intelligent industrial chain that It helps to optimize the industrial structure. Yang et al. (2022) showed that the development of digitalization can promote the transformation of industrial structure to tertiary industry, gradually eliminating old industries with high energy consumption and carbon emissions, and can improve the production technology as well as management mode of industries, and the upgrading of industrial structure is conducive to the reduction of total carbon emissions.
2) Energy consumption structure. Due to the natural resource endowment problem in China, the coal-based energy consumption structure has greatly increased carbon emissions. On the one hand, coal has become a major source of carbon emissions due to its great storage capacity and low mining cost (Jiang and Sun 2023). On the other hand, because resource-based regions may be overly dependent on energy consumption, which will eventually lead to a single resource-based industrial structure. This mono-industrial structure tends to make resource-rich regions suffer from "Dutch disease", which limits the development of manufacturing and high-tech industries. Moreover, the abundant natural resources will lead to rent-seeking behavior, resulting in the massive exploitation of resources and increasing the pressure on the ecological environment (Su and Tan 2023). For example, Wang et al. (2024c) used panel data from 69 countries to confirm that AI can effectively promote energy transition and curb carbon emissions. At the same time, many studies have shown that reducing coal consumption can reduce carbon emissions. Academics have demonstrated that green technologies, green finance, and environmental policies can drive the energy transition (Chishti et al. 2023). The data and technology elements of the digital economy can improve resource allocation efficiency and promote industrial restructuring, allowing more resources to flow to more efficient technology-intensive industries, which can also increase the market share of technology-intensive industries. The development of the digital economy could accelerate the development and use of green energy, which will become the core of the oil and

gas industry in the future (Bughin et al. 2021), thereby achieving the goal of reducing CO_2 emissions.

3) Green technology innovation. Green technology innovation is an important path to solve environmental problems. Reducing carbon emissions can be combined with advanced digital technology tools such as big data from the energy production side, energy consumption side and man-made carbon sequestration side (Ding 2021). Compared with traditional innovation, green technology innovation has the advantages of green, clean and low energy consumption. China should start from the source and encourage the development of green technology innovation, which can not only achieve sustainable development but also provide an effective path for China to achieve green and low-carbon goals (Wang et al. 2022c). The digital economy will provide support for green technology innovation, for example, digital inclusive finance can break through the time as well as space constraints of traditional financial services, which can ease the financing constraints of enterprises and provide more financial support for their green technology innovation (Liu 2022). Under the background that environmental governance has become a consensus, enterprises, as an important subject of environmental governance, should pay more and more attention to environmental responsibility (Wang et al. 2023a), digital inclusive finance is conducive to improving the efficiency of production factors of innovation subjects, reducing various costs of innovation subjects, improving the innovation environment, and reducing the financing costs of enterprises (Zhang and Hu 2023). Therefore, digital finance can motivate enterprises to do more green technology innovation work by alleviating their financing constraints and reducing financing costs. And the digital economy has given rise to a series of new industries, which provide more jobs for society. At the same time, these new industries have technical requirements for human resources, which can promote people to continuously learn and improve their quality, i.e., the digital economy can help advanced human capital structure, which can provide human support for enterprises to carry out technological innovation (Li et al. 2022b). As a whole, the development of digital economy is conducive to providing a good environment for green technological innovation.
4) Resource allocation. Under certain technical conditions, the reverse flow of factors can hinder economic development and cause efficiency losses, Correcting resource misallocation is an important way to release the potential of sustainable economic development (Chen et al. 2024). At the same time, local governments often use market segmentation in the process of competition to protect the position of local products in the market, which will in turn lead to market segmentation, and this will inevitably lead to the failure of the market operation mechanism, making it difficult for production factors to achieve free flow and the allocation of resources to be optimal. It may also be difficult for factors to flow to more efficient regions due to information asymmetry, which may lead to waste of resources (Zhang and Wang 2020). On the one hand, the digital economy can overcome the constraints of geography, time constraints and information flow, promote the digital transformation of enterprises, and use technology to link all aspects of enterprises, which can effectively solve the problem of information asymmetry and "information barriers" in the process of factor transfer. On the other hand, the digital economy is highly permeable and synergistic, which can improve the efficiency of factor allocation by promoting the integration of information and data with traditional factors (Ge et al. 2022). As Kretschmer and Khashabi (2020) argue that digitization has a positive impact on carbon efficiency by accomplishing the identification, division of labor, supervision, and reorganization of tasks, improving business efficiency and avoiding resource waste.

Based on the above analysis, the following research hypotheses are proposed:

Hypothesis 2a The digital economy reduces carbon emission intensity by optimizing the industrial structure.

Hypothesis 2b The digital economy reduces carbon emission intensity by facilitating the transformation of the energy consumption mix.

Hypothesis 2c The digital economy reduces carbon emission intensity by driving green technology innovation.

Hypothesis 2d The digital economy reduces carbon emission intensity by increasing resource allocation efficiency.

Moderating Role Between Digital Economy and Carbon Emission Intensity

1) Government intervention. Government intervention refers to government intervention and regulation of the market using legal means and economic policies, planning guidance, and administrative means to overcome market failures. As an important force affecting economic activities, government intervention has a double-edged sword effect. Although some studies have argued that government intervention leads to a reduction in the efficiency of market resource allocation

(Xiang et al. 2023), the solution of macro problems such as smooth market operation and financial risks must rely on government intervention, and achieving carbon emission reduction targets still relies on the dual role of market-led and government intervention. Nevertheless, this paper argues that government intervention will weaken the negative relationship between digital economy development and carbon emission intensity. Specifically, in recent years, there has been a phenomenon of economic comparison in different regions of China. Local governments attach great importance to economic development, and all regions are scrambling to develop the economy, because this is conducive to the performance of government officials. Local governments have become the interest subjects of regional economic development, which is bound to reduce or even ignore the concern about carbon emission reduction., and extensive economic growth is not conducive to carbon reduction. Although, the government can use environmental regulation, tax incentives, and fiscal policy to stimulate enterprises and local governments to engage in "green" activities. According to Porter's hypothesis, environmental regulation can lead to more innovative activities, the contribution of enterprise innovation to environmental performance is related to the external capital environment (Deng et al. 2022), and Ouyang et al. (2022) argue that increasing the intensity of environmental regulation can lead to higher pollution control costs, which can lead to green technological innovation activities and improved production processes. Meanwhile, Song et al. (2020) argue that R&D tax incentives have a key role in promoting green product innovation. However, if the government pays too much attention to economic development, it will inevitably ignore carbon emission reduction. Therefore, excessive government intervention may weaken the negative relationship of digital economy to carbon emission reduction.

2) Human capital. Human capital is the capital embodied in workers, which is innovative and can allocate resources efficiently. The increase in population size leads to an increase in resource consumption and human activities are seen as one of the key factors of environmental change (Zhang et al. 2021), so it is considered whether human capital controls environmental degradation. Some studies have shown that human capital can mitigate environmental degradation (Ahmed et al. 2020). Specifically, education is one of the main influencing factors of human capital, and through education, the level of technological innovation, efficiency, and quality of work done by the workforce can be improved, which can lead to the creation of more value. Zafar et al. (2019) argue that when a country has a good stock of human capital, the demand for environmental quality increases, so it needs to be improved by reducing energy consumption, conservation of natural resources and development of new technologies to improve environmental quality. The view of Zafar et al. is also shared by Çakar et al. (2021) who argue that improvement in the quality of human capital leads to environmental awareness, which can reduce carbon emissions. In addition, Çakar et al. agree that without high quality human capital, innovation is not possible, and innovation can reduce carbon emissions.

Based on the above analysis, the hypothesis can be formulated:

Hypothesis 3a Government intervention can weaken the negative relationship between strengthening the digital economy and carbon intensity.

Hypothesis 3b Human capital can reinforce the negative relationship between the digital economy and carbon emissions intensity.

Figure 3 shows the frame diagram of the research hypothesis section.

Study Design

Variable

Explained Variable: Carbon Emission Intensity (CEI)

Guo and Zhang (2023) argue that previous literature has often used the total amount method for measuring carbon emissions, but this calculation method does not reflect the carbon emission efficiency of the region well. If we simply use carbon emissions, it may lead to the more developed the digital economy, the greater its carbon emissions, and it is easier to confuse the relationship between the two. At the same time, considering that China is in the stage of development, we cannot ignore economic development while reducing emissions, so the article utilizes the ratio of carbon intensity—total carbon dioxide emissions to regional gross domestic product and takes its natural logarithm as the explanatory variable in this article. Considering the accuracy as well as comprehensiveness of the data, the authors use the carbon dioxide emissions from the China Carbon Accounting Database (CEADs) as the carbon emission level in this paper.

In order to analyze the spatial distribution characteristics of carbon emission intensity, this paper adopts the natural

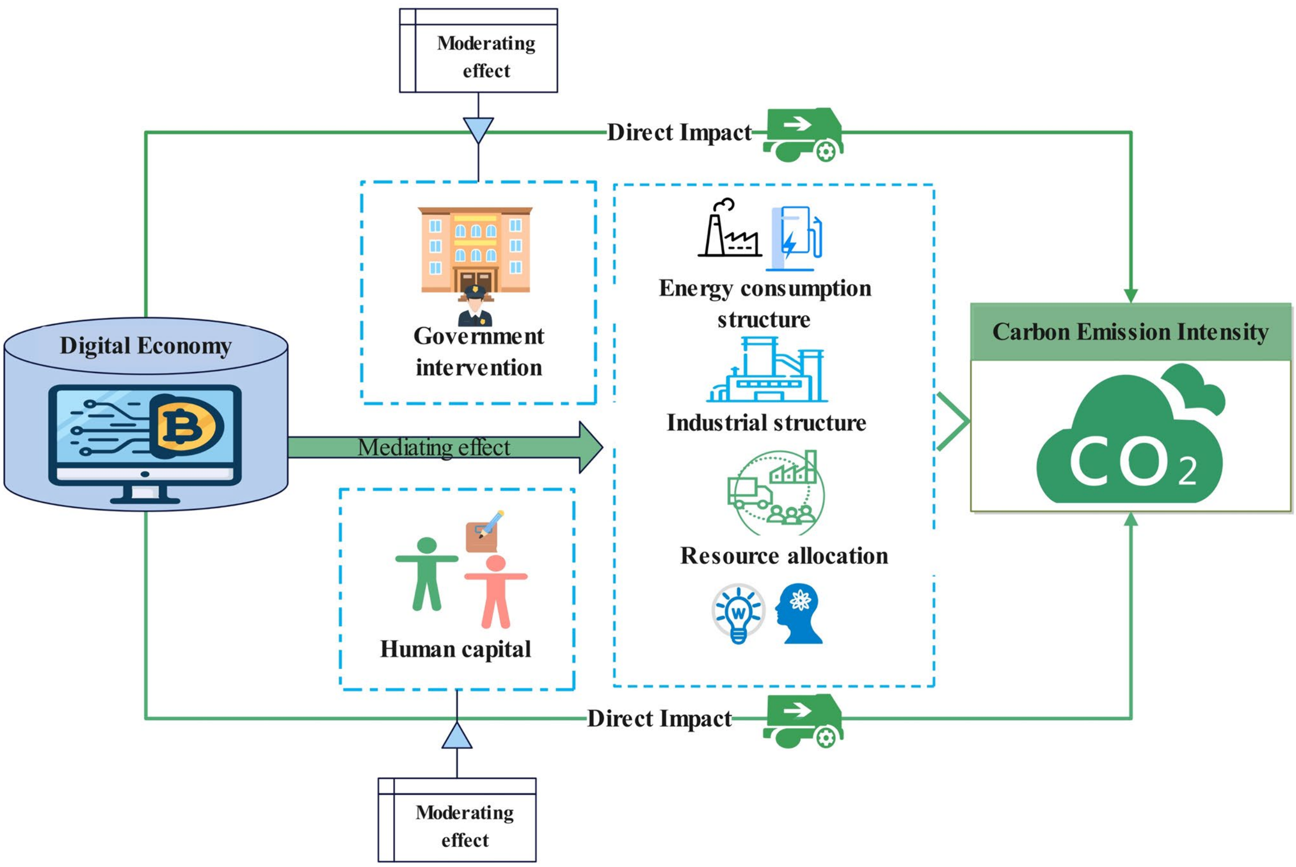

Fig. 3 Impact mechanism of digital economy on carbon emissions

breakpoint grading method to classify carbon emission intensity into five levels, and uses ArcGIS to compare and observe the carbon emission intensity of different regions in 2012, 2015, 2018 and 2021, the specific results are shown in Fig. 4. Figure 4 shows that the carbon emission intensity in the north is higher than that in the south, and there is a problem of regional imbalance. The reason for this result is that the main heat source in the north is still dominated by coal, and the industrial structure of the north and south regions are different, and the main drivers of the economy are different, and the industrial structure in the north is heavier and has relatively poorer basic conditions, which leads to the differentiation of carbon emission intensity. Figure 5 shows the evolution trend characteristics of carbon emission levels in 30 provinces from 2011 to 2021 in the time series. As can be seen from Fig. 5, the distribution pattern of carbon emission levels is relatively dispersed. The level of carbon emissions varies greatly among some provinces and cities, but on the whole, the average level of carbon emissions in each province and city shows an upward trend.

Explanatory Variables: Digital Economy (DE)

At present, there is no unified standard for measuring the level of digital economy development. Dong et al. (2022) measured the level of digital economy from three dimensions: digital economy infrastructure, digital economy innovation environment and national digital competitiveness. Wang et al. (2022a) measured the level of digital economy from four dimensions: digital economy application, digital industrialization, industrial digitization and digital innovation environment. In this paper, the index system in Table 1 is constructed, and the entropy method is used to comprehensively measure the development level of digital economy in China's provincial cities. The specific index system is shown in Table 1.

This paper uses the natural breakpoint grading method to classify the level of digital economy into 5 levels, and uses ArcGIS to compare and observe the level of digital economy in different regions in 2012, 2015, 2018 and 2021, and the specific results are shown in Fig. 6. The results show that the development of digital economy is extremely uneven across provinces in China, and the cities with higher digital economy are mainly distributed in the eastern

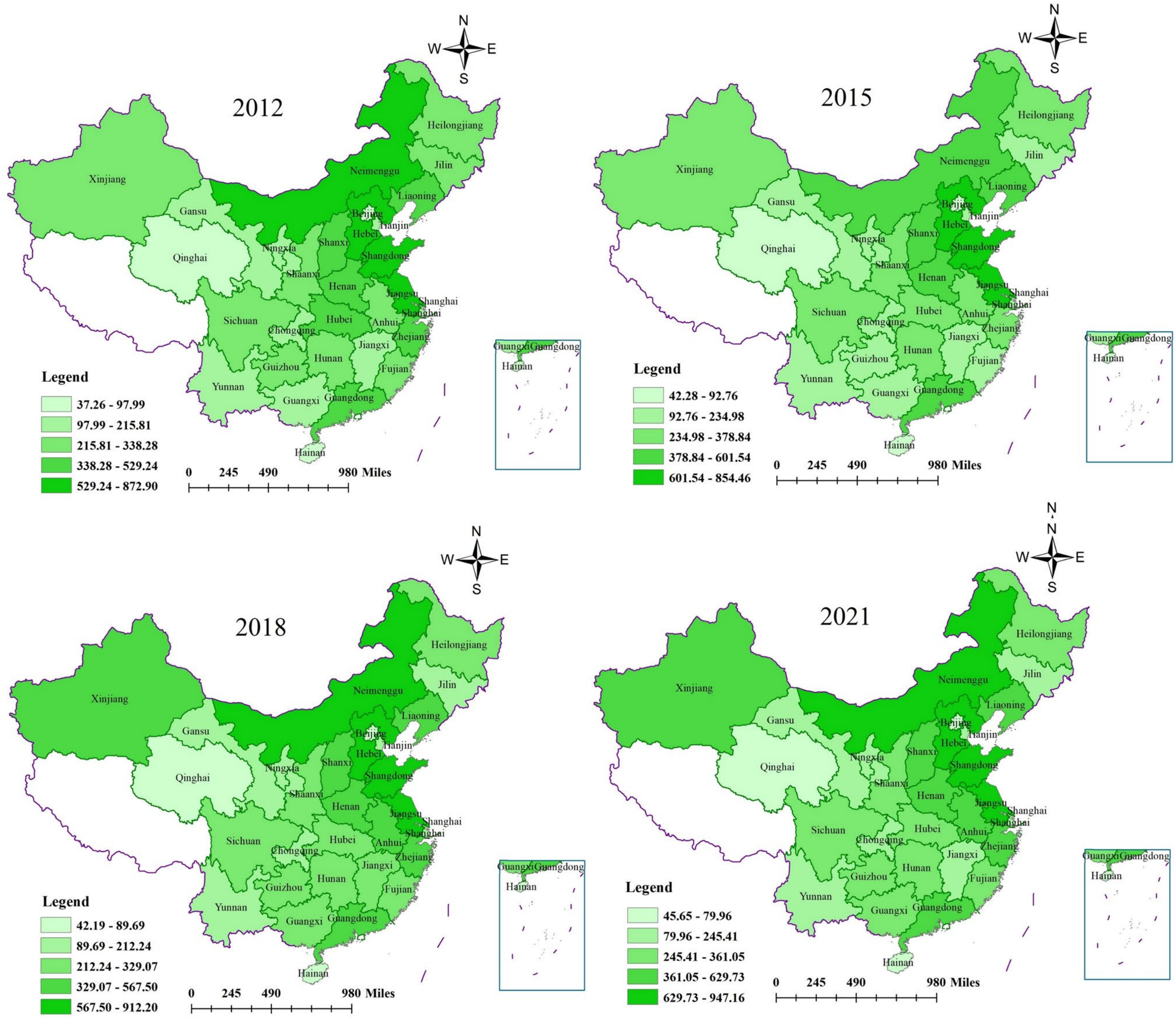

Fig. 4 Spatial distribution characteristics of carbon emission intensity

region and the south, with an overall trend of east > The overall trend is east > central > west and northeast. Beijing, Shanghai, Guangdong, Zhejiang and Jiangsu have the highest level of digital economy. The reason for this is that cities such as Beijing and Shanghai have the leading role as comprehensive leading cities in China's digital economy. Figure 7 illustrates the evolutionary trend characteristics of the digital economy development level in time series. The digital economy development level shows a distribution pattern of concentrated median values and dispersed extreme values. As can be seen from Fig. 7, the level of digital economy varies greatly among some provinces and cities, but on the whole, the average level of digital economy development of provinces and cities shows an upward trend.

Mediating Variables

In order to further explore the internal mechanism of the relationship between digital economy and carbon emission reduction, this paper selects industrial structure, energy consumption structure, green technology innovation and resource mismatch as mediating variables to explain the mechanism of the relationship between digital economy and carbon emission reduction. The ratio of the total output value of the secondary industry to the regional GDP is chosen to measure the industrial structure because the secondary industry produces the largest proportion of carbon dioxide emissions among all industries. China's "coal-rich, oil-poor, gas-poor" resource endowment makes coal occupy a large proportion of the energy consumption structure in China,

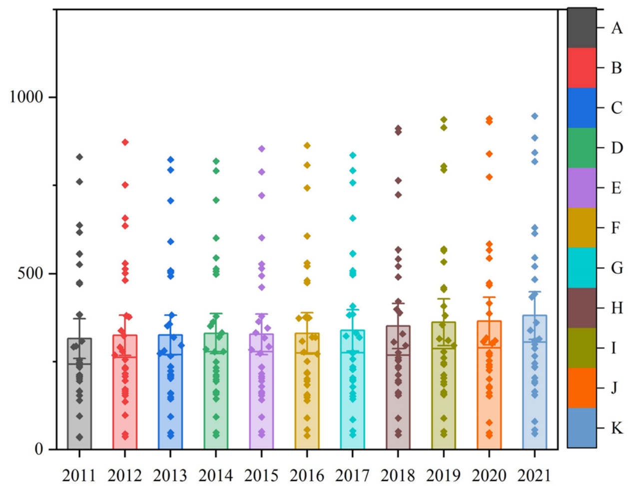

Fig. 5 Characteristics of the evolutionary trend of regional carbon emission intensity

forming an energy consumption pattern dominated by coal. Therefore, this paper selects the ratio of coal consumption to energy consumption to measure the energy consumption structure. Drawing on the study of green technology innovation by Fan et al. (2020), the article uses "pollution control, pollution treatment, environmental materials, alternative energy, energy saving and emission reduction, green agriculture, green forestry, recycling, new energy, green building, green management" as keywords to search for green patents in the patent search and analysis system of the China National Intellectual Property Administration. The number of green patent applications is used to measure the green technology innovation. The fundamental goal of resource allocation is to optimize the resources, so that the limited resources can bring out the maximum benefit and thus promote the development of economy and society. According to Hao et al. (2020), this paper constructs labor mismatch index and capital mismatch index, and the absolute distortion coefficients of both are defined as:

$$\gamma_k = \frac{1}{1+\tau_{ki}}\gamma L = \frac{1}{1+\tau_{Li}} \tag{1}$$

However, since the absolute distortion coefficients of factors cannot be measured in practice, the relative distortion coefficients of capital and labor will be used to measure the degree of factor mismatch, which is calculated as follows:

$$\widehat{\gamma_K} = \left(\frac{K_i}{K}\right) \Big/ \left(\frac{S_i\beta_{ki}}{\beta_k}\right), \widehat{\gamma_L} = \left(\frac{L_i}{L}\right) / \left(\frac{S_i\beta_{Li}}{\beta_L}\right) \tag{2}$$

Among them,si denotes the share of output yi of region in total output Y,$\beta k = \sum_i^n si\beta ki$ denotes the output-weighted value of capital, $\frac{K_i}{K}$ denotes the actual proportion of capital used in region i to total capital, $\frac{S_i\beta_{ki}}{\beta_k}$ denotes the theoretical proportion of capital used in region i when capital is used efficiently, $\widehat{\gamma_k}$ then reflects the extent to which the actual capital used deviates from the capital used at efficient allocation. Same reason, $\beta_L = \sum_i^n S_i\beta_{Li}$ denotes the output-weighted value of the labor force, $\frac{L_i}{L}$ denotes the actual ratio of the labor force used in region i to the total labor force, $\frac{S_i\beta_{Li}}{\beta_k}$ denotes the theoretical proportion of labor used in region i at the time of effective labor utilization. $\widehat{\gamma_L}$ Reflects the extent to which the actual amount of labor used deviates from the amount of labor used at the time of effective allocation. When $\hat{\gamma}$ is greater than 1, it means that the region is over-allocated to capital or labor, and conversely, if $\hat{\gamma}$ is less than 1, it means that the region is under-allocated to capital or labor.

According to Bai et al. (2018), this paper uses the Solow residual method to measure β_{ki}, β_{Li}. The production function is

Table 1 Comprehensive index system of digital economy development level

Dimension	Indicator name
Digital economy development	Internet broadband access users
	Permanent population at the end of the year
	Employment in information transmission, software and information technology services in urban units
	People employed in urban units
	Total volume of telecommunication service
	Mobile phone year-end users
	Digital Financial Inclusion Index
	Internet users per 100 people
	Share of employees in information transmission, computer services and software industries
	Total telecommunications services per capita
	Number of mobile phone users per 100 people

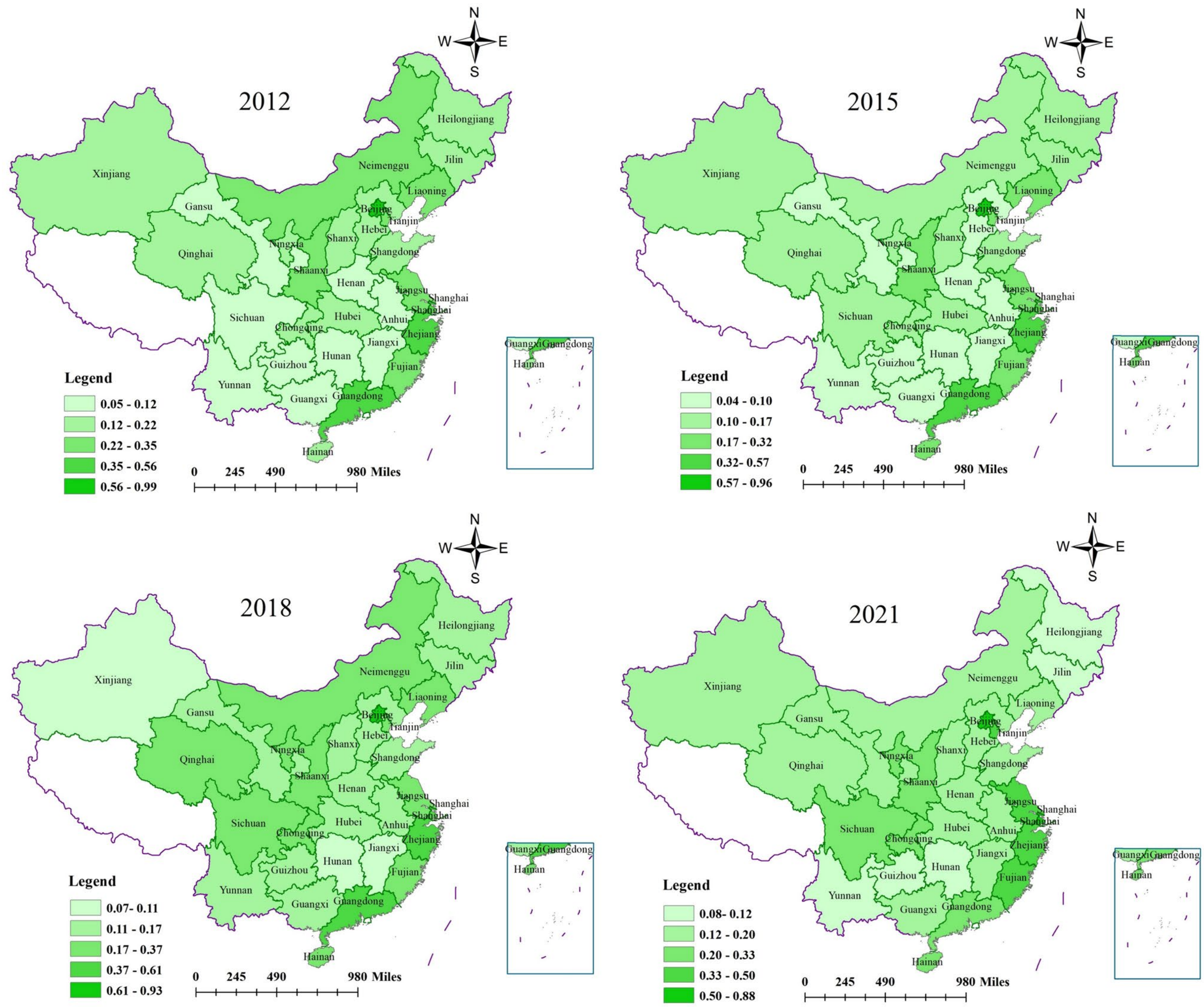

Fig. 6 Spatial distribution of digital economy development level

assumed to be a C-D production function with constant returns to scale, and the expression is:

$$Y_{it} = AK_{it}^{\beta_{ki}} L_{it}^{1-\beta_{ki}} \quad (3)$$

Taking logarithms on both sides of the equation simultaneously and controlling for time effects λt and individual effects μi in the model, the collation yields:

$$\ln \left(Y_{it} / L_{it} \right) = \ln A + \beta_{ki} \ln \left(K_{it} / L_{it} \right) + \lambda_t + \mu_i + \varepsilon_{it} \quad (4)$$

where Kt is expressed in terms of the real GDP of each province, using 2000 as the base period and converting the GDP of other years into real GDP expressed in constant 2000 prices. this paper uses the number of employed persons in each province to denote Y_{it}. Using the capital stock of each province to denote K_{it}, and using the perpetual inventory method to calculate it, the formula is as follows:

$$K_t = \left(1 - d_t\right) + \frac{I_t}{P_t} \quad (5)$$

Kt denotes fixed capital stock, It denotes fixed capital investment amount, Pt denotes the fixed asset investment price index, and δt is the depreciation rate, which is taken as 10.96% by Shan (2008). For the calculation of the capital stock in the base period, the article draws on the approach of Shan, and this paper uses the sum of the actual fixed capital investment in each province in 2000 over the depreciation rate of 10.96% and the average of the investment growth rate during 2001–2005, which is calculated as:

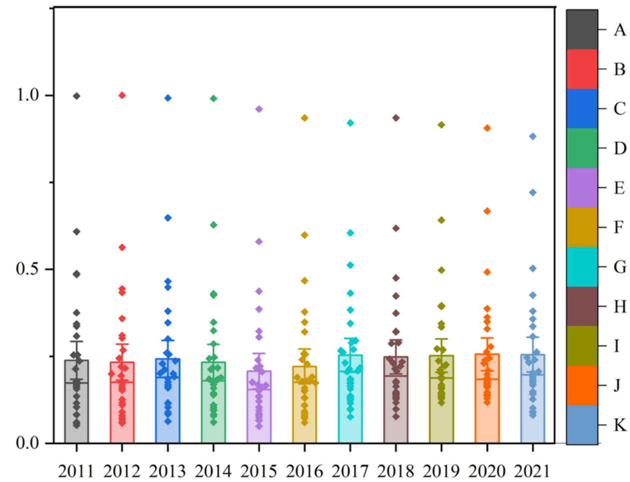

Fig. 7 Digital economy development level evolutionary trend characteristics

$$K_0 = \frac{I_1}{10.96\% + g} \tag{6}$$

$I1$ denotes the actual fixed capital investment in each province in 2001, using 2000 as the base period, and g denotes the average investment growth rate over the period 2001–2005.

Control Variables

In the actual situation, in addition to the independent variable will have an impact on the dependent variable, there will be other factors affecting the dependent variable. If we ignore the influence of these variables, it will cause endogeneity problems. Their existence will interfere with researchers' analysis of the influence of independent variables on dependent variables, which usually needs to be controlled in the experiment to ensure the accuracy of experimental results. Existing studies have analyzed the influencing factors of environmental pollution from different perspectives, and the main influencing factors focus on environmental regulation, foreign direct investment, urbanization, economic development level, international trade, and economic agglomeration (Shi et al. 2018), population size (Wang et al. 2017), R&D investment (Li et al. 2021), carbon sink (Lin et al. 2019), transportation (Bai et al. 2023), and nature reserves (Zhang et al. 2023a). To avoid the influence of other factors on the empirical results, the article selects environmental regulation, resource endowment, urbanization level, economic development level, population size, trade openness, R&D investment and foreign direct investment, carbon sink, transportation, nature reserve and Low carbon pilot city as control variables. Resource endowment theory proposes that the relative differences in factor endowments determine the differences in production costs of goods, and such relative differences also constitute comparative advantage. In this paper, the resource endowment coefficient is used to measure the resource endowment of each region. A larger resource endowment coefficient indicates the relative abundance of that resource. This paper indicates the resource endowment of regions in terms of labor, technology and capital factors. The working age sample population is used to represent the labor factor, the industrial R&D above the scale to represent the technology factor, and the capital stock to represent the capital factor. The calculation formula:

$$EF_{ij} = \frac{e_{ij}/E_i}{y_j/Y} \tag{7}$$

where e_{ij} denotes the amount of resource i in province j, E_i denotes the total national resource of resource i, y_j, denotes the GDP of province j, and Y denotes the national GDP.

Table 2 shows the definition of the variable.

Data Source

The article considers the comprehensiveness of the data and the fact that the digital economy has developed more rapidly in recent years, so the research period is determined to be 2011–2021. Since Tibet, Hong Kong, Macau and Taiwan have more missing data, they are excluded, and 30 Chinese provinces and cities are taken as the research objects of this article. Among them, carbon dioxide emission data are obtained from the CEADs, the provincial carbon dioxide emission inventory provided by this database covers 47 socioeconomic sectors and 17 fossil fuel combustion and cement production-related process emissions according to the IPCC sectoral accounting method, ensuring the accuracy of the carbon dioxide emission data (Shan et al. 2018; Shan et al. 2020; Guan et al. 2021; Shan et al. 2016). and data of some variables are obtained from CSMAR, China's provincial and municipal statistical yearbooks, China Science and Technology Statistical Yearbook and China Environmental Statistical Yearbook. The digital financial inclusion index is adopted from Guo et al. (2020) compiled by the digital financial inclusion index is indicated, and the data related to legal environmental regulation are obtained from Peking University Law Information Database. With the keywords of "pollution control, pollution treatment, environmental materials, alternative energy, energy saving and emission reduction, green agriculture, green forestry, recycling, new energy, green building, green management", the paper searched for green patents in the patent search and

Table 2 Definition of variables

	Primary index	Secondary index	Definition	Abbreviation
Explained variable	Carbon emission intensity		Ratio of total carbon emissions to GDP	*CEI*
Explanatory variable	Digital economy		Measurement of comprehensive index system	*DE*
Mediating variable	Industry structure		ratio of total secondary industry output to regional GDP	*IS*
	Energy consumption structure		Ratio of coal consumption to energy consumption	*ECS*
	Green technology innovation		Number of green patent applications	*GTI*
	Resource allocation	Labor mismatch	Labor mismatch index	*abstaul*
		Capital mismatch	Capital mismatch index	*abstauk*
Adjustment variable	Government intervention		General public budget expenditure as a share of GDP	*Gov*
	Human capital		Measurement of comprehensive index system	*Humc*
Control variable	FDI		Total Foreign Investment	*FDI*
	Economic development		GDP per capita	*PGDP*
	Urbanization level		Number of urban population to total population	*UL*
	Trade openness		Ratio of total regional exports and imports to regional GDP	*TO*
	Environmental regulation	Economic environmental regulation	Ratio of industrial pollution control investment to industrial value added	*ERA*
		Legal environmental regulation	Number of environmental administrative penalties	*ERB*
		Supervised environmental regulation	Environmental monitoring operational expenses	*ERC*
	Elemental Endowment	Labor endowment	Number of working age sample population	*LRE*
		Technology endowment	Industrial R&D above the scale	*TRE*
		Capital endowment	Capital stock	*CRE*
	Population size		Total population at the end of the year	*Pop*
	R&D investment		Ratio of internal expenditure of R&D funds to GDP	*RD*
	Carbon sink		Forest cover	*CS*
	Transportation		Operating mileage of roads and railroads	*Trans*
	Nature reserves		National nature reserve area	*NR*
	Low carbon pilot city		Low carbon pilot city	*Lcpc*

analysis system of the State Intellectual Property Office. In this paper, the logarithmic values of each index data are taken for analysis, and for individual missing values, linear interpolation method is used for processing.

Methods and Models

Spatial Econometric Model

Spatial Autocorrelation Analysis Before conducting spatial econometric analysis, spatial autocorrelation tests must be performed. In this paper, the spatial autocorrelation test of regional carbon emissions is carried out using the global Moran index, and the specific expression is (Xu et al. 2022):

$$I = \frac{n\sum_{i=1}^{n}\sum_{j=1}^{n} W_{i,j}\left|X_i - \overline{X}\right|\left|X_j - \overline{X}\right|}{\sum_{i=1}^{n}\sum_{j=1}^{n} W_{i,j}\sum_{i=1}^{n}\left|X_j - \overline{X}\right|} \tag{8}$$

Among them, x denotes the carbon emission intensity, denotes the average level of carbon emission intensity, denotes the spatial weight matrix, and n denotes the sum of all studied objects. In this paper, the inverse distance spatial weight matrix is used to reflect the spatial association. The specific expressions are:

$$\mathrm{W}_{\mathrm{i,\,j}} = \begin{cases} 1/d(i \neq j) \\ 0(i = j) \end{cases} \tag{9}$$

Among them, d indicates the geographical distance between the two cities.

When the Moran's I is greater than 0, it means that the regions are spatially positively correlated; when the Moran's I is less than 0, it means that the regions are spatially negatively correlated; when the Moran's I is equal to 0, it means that there is no spatial correlation between the regions. The values of Moran's I calculated in this paper are shown in Table 3. The results show that the Moran's I are significantly greater than 0, indicating that the carbon emission intensity of each region is spatially autocorrelated.

Spatial Durbin Model According to the theoretical research above, carbon emission intensity and digital economy are selected as dependent variables and independent variables respectively in this paper. In order to test the influence of digital economy on carbon emission intensity, regression model can be used for testing. However, the traditional regression model ignores the spatial dependence characteristics of spatial data, but according to the results of spatial autocorrelation analysis, there is a significant spatial autocorrelation of carbon emission levels in each province, which cannot be ignored when studying the influencing factors of carbon emission. Our common spatial metrology models include spatial autoregressive model, spatial error model and spatial Durbin model, etc. Therefore, in this paper, after passing the Hausman test, LM test, LR test and Wald test, we choose the most suitable method for this paper, namely the spatial Durbin model. The goal of spatial Durbin model research is to help us better understand the relationship between the elements. The specific model is as follows:

Table 3 Carbon intensity global Moran index

Year	I	E(I)	sd(I)	z	p-value
2011	0.067	– 0.034	0.032	3.131	0.001
2012	0.081	– 0.034	0.033	3.457	0.000
2013	0.078	– 0.034	0.033	3.379	0.000
2014	0.083	– 0.034	0.033	3.523	0.000
2015	0.090	– 0.034	0.034	3.663	0.000
2016	0.067	– 0.034	0.035	2.928	0.002
2017	0.035	– 0.034	0.035	1.989	0.023
2018	0.040	– 0.034	0.035	2.151	0.016
2019	0.038	– 0.034	0.035	2.087	0.018
2020	0.088	– 0.034	0.033	3.713	0.000
2021	0.089	– 0.034	0.033	3.742	0.000

$$\ln CEI_{i,t} = \rho\sum_{j=1}^{n} W_{ij}\ln CEI_{i,t} + \alpha_0\beta_1\ln X_{i,t} + \sum_{j=1}^{n} W_{i,j}\ln X_{i,t\gamma} + \mu_i + \lambda_t + \varepsilon_{i,t} \tag{10}$$

Among them, $CEI_{i,t}$ denotes the carbon emission level of each province in different periods; $X_{i,t}$ denotes the explanatory variables with core explanatory variables and control variables; ρ denotes the spatial lagged regression coefficient of the explained variables; α_0 denotes the intercept term; β_1 denotes the coefficient of the explanatory variables; γ denotes the spatial lagged regression coefficient of the explanatory variables; μ_i denotes the individual effect; λ_t denotes the time effect; $\varepsilon_{\mathrm{i,t}}$ denotes the random disturbance term.

Mediating Effect Model

In the theoretical analysis, it is considered that industrial structure, energy consumption structure, green technology innovation and resource allocation will play an intermediary role in the relationship between digital economy and carbon emission intensity. Therefore, this paper draws on Wen (2014) practice to build an intermediary effect model. The specific model is as follows:

$$\ln CEI_{i,t} = \rho\sum_{j=1}^{n} W_{ij}\ln CEI_{i,t} + \alpha_2\beta_2\ln X_{i,t} + \sum_{j=1}^{n} W_{i,j}\ln X_{i,t}\gamma + \mu_i + \lambda_t + \varepsilon_{i,t} \tag{11}$$

$$\ln CEI_{i,t} = \rho\sum_{j=1}^{n} W_{ij}\ln CEI_{i,t} + \alpha_3 + \beta_3\ln X_{i,t} + \sum_{j=1}^{n} W_{i,j}\ln X_{i,t}\gamma + \mu_i + \lambda_t + \varepsilon_{i,t} \tag{12}$$

$$\ln CEI_{i,t} = \rho \sum_{j=1}^{n} W_{ij} \ln CEI_{i,t} + \alpha_4 + \beta_4 \ln X_{i,t} + \beta_5 \ln X_{i,t} + \sum_{j=1}^{n} W_{i,j} \ln X_{i,t}\gamma_1 + \sum_{j=1}^{n} W_{i,j} \ln M_{i,j}\gamma_2 + \mu_i + \lambda_t + \varepsilon_{i,t} \quad (13)$$

Among them, Mi,t denotes the mediating variable. Using stepwise regression to determine the presence or absence of mediating effects. First, the significance of the test coefficient β_2. Second, the significance of the test coefficient β_3, β_5. If both of these conditions are satisfied, the mediating effect exists. Figure 8 shows mediating effect mechanism.

Threshold Effect Model

This paper aims to explore whether there is only a nonlinear relationship between digital economy and carbon emission intensity, that is, whether there is an inflection point between digital economy and carbon emission intensity in the regression. Therefore, the threshold effect model is used for testing. The idea of single threshold regression in the threshold model is that when there is a threshold level γ for an influential variable qi in the model, there is a significant difference between $q_{i,t} > \gamma$ and $q_{i,t} < \gamma$ in their influence on the explained variable. The specific model is as follows:

$$\ln CEI = \varphi \ln X_{i,t} I(q_{i,t} \le \gamma) + \varphi_2 \ln X_{i,t} I(q_{i,t} > \gamma) + \mu_{i,t} + e_{i,t} \quad (14)$$

Among them, $q_{\mathrm{i,t}}$ is the threshold variable; γ is the threshold value; $(\cdot)$ is the demonstrative function.

Empirical Results and Discussion

Regression Results Effect Analysis

The article introduces the spatial Durbin model to explain the effect of digital economy on carbon emission intensity. The calculation results are shown in Table 4. Model2 and Model3 in Table 4 show that the development of digital economy has a significant negative effect on carbon emission intensity, and Hypothesis 1 is verified.

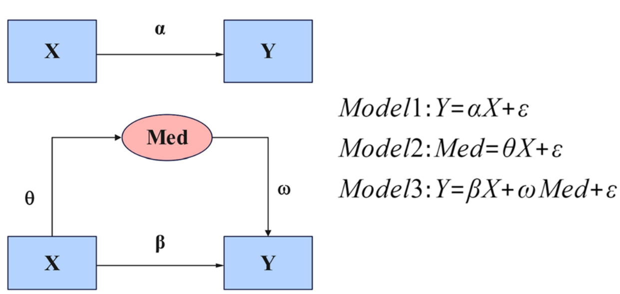

Fig. 8 Mediating effect mechanism

However, among the above three models, only Model1 has a significant spatial spillover effect. In Model3, digital economy can significantly reduce the carbon emission intensity of the region. With the deepening of the digital economy, the region has not only improved its innovation capabilities, but also accelerated the greening and intelligent transformation of traditional industries. The application of digital tools and technologies makes production processes more efficient, reducing resource waste and environmental pollution, while promoting the use of clean energy and reducing carbon intensity. At the same time, the development of the digital economy has spawned a series of new industries with low energy consumption and high added value, such as cloud computing, big data, artificial intelligence, etc. The rise of these industries has replaced the traditional industrial sectors with high pollution and high energy consumption, thus optimizing the industrial structure and realizing the decoupling of economic growth and carbon emissions. Moreover, the development of the digital economy has enhanced the governance capacity of the government, enabling it to implement carbon emission trading, carbon tax and other policies more effectively, monitor corporate carbon emissions, and encourage enterprises to adopt energy conservation and emission reduction measures, which has further promoted the reduction of carbon emission intensity. However, it is worth noting that the expansion of the digital economy also brings new challenges. Although the development of digital economy in this region has a significant inhibitory effect on its own carbon emission intensity, it may have a negative spillover effect on neighboring regions. This is because neighboring regions, in order to catch up with the development of the digital economy, may accelerate the construction of infrastructure, resulting in increased energy consumption and rising carbon emissions in the short term. This phenomenon reminds us that while promoting the development of the digital economy, we need to take into account cross-regional synergies, avoid the emergence of a "digital divide", and jointly promote green and low-carbon transformation through regional cooperation and policy coordination to achieve the sustainable development goals. To sum up, the digital economy shows great potential in reducing carbon intensity, but its impact does not exist in isolation, and regional interactions and overall environmental impacts need to be considered comprehensively to ensure that the healthy development of the digital economy goes hand in hand with environmental protection.

We tried to use qualitative analysis to verify the inhibition effect of digital economy on carbon emission intensity again. For example, the first batch of pilot cities for the digital transformation of smes was announced in

Table 4 Spatial model regression results

Variance	(1) Model 1		(2) Model 2		(3) Model 3	
	Main	W.x	Main	W.x	Main	W.x
ln*DE*	0.176**	1.474***	– 0.153***	0.018	– 0.149***	0.216
	(0.0413)	(0.004)	(0.000)	(0.940)	(0.000)	(0.480)
ln*FDI*	– 0.111*	– 1.128**	0.001	– 0.199	– 0.042	– 0.765***
	(0.0876)	(0.032)	(0.967)	(0.308)	(0.234)	(0.008)
ln*PGDP*	– 0.251*	0.865	– 0.656***	– 0.745**	– 0.657***	– 0.819*
	(0.0545)	(0.352)	(0.000)	(0.041)	(0.000)	(0.087)
ln*UL*	4.131***	26.032***	0.368	– 0.656	0.472	– 3.112
	(0.000)	(0.000)	(0.364)	(0.753)	(0.282)	(0.326)
ln*TO*	– 0.090**	– 0.163	– 0.028	0.183	– 0.026	0.177
	(0.0471)	(0.707)	(0.330)	(0.242)	(0.373)	(0.419)
ln*ERA*	0.193***	0.291	0.002	0.002	0.003	0.080
	(0.000)	(0.201)	(0.842)	(0.969)	(0.794)	(0.385)
ln*ERB*	0.006	– 0.030	– 0.005***	– 0.003	– 0.005***	– 0.005
	(0.1329)	(0.284)	(0.000)	(0.613)	(0.000)	(0.673)
ln*ERC*	– 0.003	– 0.07	– 0.001	0.042	0.006	0.082
	(0.8611)	(0.956)	(0.911)	(0.301)	(0.385)	(0.115)
ln*LRE*	0.247***	0.601	0.095**	– 0.085	0.105**	– 0.529**
	(0.004)	(0.212)	(0.023)	(0.671)	(0.011)	(0.045)
ln*TRE*	– 0.398***	– 5.065***	0.218***	– 0.176***	0.216***	0.054
	(0.000)	(0.000)	(0.000)	(0.005)	(0.000)	(0.903)
ln*CRE*	1.065***	4.819***	0.610***	1.097***	0.596***	0.786
	(0.000)	(0.000)	(0.000)	(0.001)	(0.0000)	(0.1214)
ln*Pop*	– 0.301*	– 0.574	0.735*	– 8.00 5***	1.078**	– 6.239**
	(0.0716)	(0.610)	(0.099)	(0.007)	(0.022)	(0.049)
ln*Trans*	0.700***	4.509***	0.133	1.926	0.141	1.725
	(0.000)	(0.000)	(0.457)	(0.189)	(0.465)	(0.312)
ln*CS*	– 0.122***	– 0.288	– 0.046	0.977*	0.014	1.919**
	(0.001)	(0.495)	(0.686)	(0.051)	(0.904)	(0.020)
ln*Humc*	– 1.629***	– 9.218***	0.013	0.175	0.040	– 0.264
	(0.000)	(0.000)	(0.916)	(0.819)	(0.767)	(0.820)
ln*NR*	– 0.272***	– 1.973***	– 0.065	0.999	– 0.148*	0.061
	(0.000)	(0.000)	(0.419)	(0.178)	(0.071)	(0.936)
Lcpc	– 0.118*	– 0.934	0.010	0.056	0.018	0.238
	(0.073)	(0.132)	(0.699)	(0.445)	(0.546)	(0.347)
Time fixed	Yes		No		Yes	
Regional fixed	No		Yes		Yes	
Double fixed	No		No		Yes	
N	330		330		330	

Notes: *, **, and *** represent the significance at 10%, 5%, and 1% levels, respectively

2023, aiming to guide and promote the transformation of smes through demonstration, replication and promotion, and comprehensively improve the digital level of smes. Among the pilot cities, the carbon emission intensity of Suzhou, Shenzhen and Hangzhou is at a very low level in the whole country. This result is expected to be consistent with the results of the paper, which indicates that the digital economy can reduce the carbon emission intensity. In addition, Guan Dabo, a professor at Tsinghua University and an academician of the British National Academy of Social Sciences, said in an interview with reporters that digital transformation and low-carbon transformation are complementary to each other, and in the process of a series of social production relations guided by carbon neutrality, digitalization will play an irreplaceable carrier role.

Table 5 Results of intermediary effect analysis

Variable	(1) ln*CEI*	(2) ln*IS*	(3) ln*CEI*	(4) ln*ECS*	(5) ln*CEI*	(6) ln*GTI*	(7) ln*CEI*	(8) ln*abstauk*	(9) ln*CEI*	(10) ln*abstaul*	(11) ln*CEI*
ln*DE*	– 0.122*** (0.000)	– 0.057* (0.000)	– 0.103*** (0.000)	– 0.246*** (0.000)	– 0.097*** (0.000)	0.251* (0.065)	– 0.101*** (0.000)	– 0.178** (0.046)	– 0.070*** (0.003)	– 0.263* (0.066)	– 0.105*** (0.001)
ln*IS*			0.483*** (0.000)								
ln*ECS*					0.154*** (0.000)						
ln*GTI*							– 0.019* (0.057)				
ln*abstauk*									0.024* (0.083)		
ln*abstaul*											– 0.039** (0.063)
W.ln*DE*	0.015 (0.9428)	– 0.118 (0.272)	0.153 (0.452)	– 1.049*** (0.010)	0.145* (0.458)	2.499* (0.012)	– 0.064 (0.759)	– 0.033 (0.946)	– 0.157 (0.384)	1.847* (0.078)	– 0.126 (0.631)
W.ln*IS*			2.874 (0.000)								
W.ln*ECS*					– 0.002 (0.986)						
W.ln*GTI*							0.110 (0.106)				
W.ln*abstauk*									0.274*** (0.002)		
W.ln*abstaul*											– 0.386*** (0.004)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: *, **, and *** represent the significance at 10%, 5%, and 1% levels, respectively

Therefore, the digital economy does have a restraining effect on carbon emission intensity.

Mediating Effect Analysis

To test the mediating role of industrial structure, energy consumption structure, green technology innovation and resource allocation in the impact of digital economy on carbon emission intensity, empirical tests are conducted in this part. The specific calculation results are shown in Table 5.

As can be observed from the regression results in Table 5, columns 1–3 analyze the mediating effect of industrial structure between the digital economy and carbon emission intensity. Column 1 indicates that there is a significant negative correlation between the digital economy and carbon emission intensity, i.e., β_2 in Eq. 11 is significant. Column 2 indicates that the digital economy has a significant negative effect on the industrial structure (the share of secondary industry), i.e., β_3 in Eq. 12 is significant. Column 3 indicates that both the digital economy and the industrial structure have a significant hindering effect on carbon emission intensity, i.e., β_4 and β_5 in Eq. 13 are significant. Thus, it can be judged that there is a mediating effect of industrial structure in the influence of digital economy on carbon emission intensity. The digital economy reduces carbon emission intensity by promoting the upgrading of industrial structure, and when the digital economy increases by 1%, the proportion of the secondary industry will decrease by 0.057%, hypothesis 2a is verified. Column 1 and columns 4–5 in Table 5 analyze the mediating effect of energy consumption structure between the digital economy and carbon emission intensity. Column 4 indicates that the digital economy has a significant inhibitory effect on the energy consumption structure (coal consumption share), i.e., β_2 in Eq. 12 is significant; column 5 indicates that there is a significant effect of both the digital economy and the energy consumption structure on the carbon emission intensity, i.e., β_4 and β_5 in Eq. 13 are significant. From the basis of the judgment of the existence of the mediating effect, there is a mediating effect of energy consumption structure between the digital economy and carbon emission intensity. At the same time, Digital economy promotes the transformation of energy consumption structure to clean energy consumption in order to reduce carbon emission intensity, and a 1% increase in digital economy will reduce the proportion of coal consumption by 0.224%, hypothesis 2b is verified. Column 1 and columns 6–7 in Table 5 analyze the mediating effect of green technology innovation between the digital economy and carbon emission intensity. Column 6 indicates that the digital economy has a significant promotion effect on green technology innovation, i.e., β_2 in Eq. 12 is significant; column 7 indicates that both the digital economy and green technology innovation have significant effects on carbon emission intensity, i.e., β_4 and β_5 in Eq. 13 are significant, thus it can be judged that there is a mediating effect of green innovation technology between the digital economy and carbon emission intensity. It can also be obtained that the digital economy reduces the carbon emission intensity by promoting the innovation of green technology, and hypothesis 2c is verified. Column 1 and Columns 8–11 in Table 5 analyze whether there is a mediating effect of resource allocation between the digital economy and carbon emission intensity. Columns 8–9 are for testing the mediating effect of the capital mismatch index, and columns 10–11 are for testing the mediating effect of the labor mismatch index. Column 8 and column 10 indicate that the digital economy has a significant inhibitory effect on both capital mismatch index and labor mismatch index, i.e., β_2 in Eq. 12 is significant. Meanwhile, column 9 and column 11 indicate that the digital economy, labor mismatch index and labor mismatch index have significant effects on carbon emission intensity, i.e., β_4 and β_5 in Eq. 13 are significant, so it can be determined that there is a mediating effect of resource allocation between digital economy and carbon emission intensity. There is a mediating effect between the digital economy and carbon emission intensity. Moreover, the digital economy can optimize resource allocation to reduce carbon emissions intensity, and hypothesis 2d is verified.

Regulation Effect Analysis

Table 6 illustrates that the digital economy (ln*DE*) can regulate the degree of influence on carbon emission intensity through government intervention (ln*Gov*) and human capital (ln*Humc*). Table 6 illustrates that there is a positive moderating effect of government intervention (ln*Gov*) and human capital (ln*Humc*) on the relationship between digital economy and carbon emission intensity, so hypothesis 3a and 3b are verified. This suggests that the degree of negative impact of the digital economy on carbon emissions intensity is stronger when the degree of government intervention is higher or the structure of human capital is more advanced. It may be because when the government intervention is higher and the human capital is more advanced, the innovation effect generated will be greater. Innovation is the first driving force for development, and innovation can not only promote the development of clean technology and digital technology, but also optimize the allocation of resources and promote the flow of factors, so it should have a positive moderating effect between the digital economy and carbon emission intensity.

Table 6 Moderating effect results

ln*CEI*	Government intervention			Human capital		
	(1)	(2)	(3)	(4)	(5)	(6)
Main						
ln*DE*	– 0.128***	– 0.073	– 0.138***	– 0.131***	0.830**	– 0.145***
	(0.000)	(0.103)	(0.000)	(0.000)	(0.036)	(0.000)
ln*Gov*	0.089	0.131*	0.131*			
	(0.218)	(0.093)	(0.093)			
ln*DE**ln*Gov*		0.042*				
		(0.077)				
ln*DE**c_ln*Gov*			0.042*			
			(0.077)			
ln*Humc*				0.169*	0.014	0.014
				(0.073)	(0.908)	(0.908)
ln*DE**ln*Humc*					– 0.072**	
					(0.015)	
ln*DE**c_ln*Humc*						– 0.072**
						(0.015)
Wx						
ln*DE*	– 0.174*	– 0.508***	– 0.112	– 0.169	– 5.385**	– 0.105
	(0.054)	(0.009)	(0.243)	(0.112)	(0.017)	(0.345)
ln*Gov*	0.171	– 0.253	– 0.253			
	(0.550)	(0.490)	(0.490)			
ln*DE**ln*Gov*		– 0.257*				
		(0.058)				
ln*DE**c_ln*Gov*			– 0.257*			
			(0.058)			
ln*Humc*				-0.188	0.456	0.456
				(0.723)	(0.455)	(0.455)
ln*DE**ln*Humc*					0.391**	
					(0.021)	
ln*DE**c_ln*Humc*						0.391**
						(0.021)
Control Variable	Yes	Yes	Yes	Yes	Yes	Yes
N	330	330	330	330	330	330

Notes: *, **, and *** represent the significance at 10%, 5%, and 1% levels, respectively

Table 7 Threshold effect test

Threshold variable	Single threshold			Double threshold		
	Threshold value	F-value	P-vlaue	Threshold value	F-value	P-vlaue
ln*TRE*	– 2.286	226.09	0.000	0.553	130.37	0.000
ln*LRE*	– 1.466	335.39	0.000	– 0.171	226.19	0.000
ln*CRE*	– 1.387	335.5	0.000	–	–	–

Threshold Effect Analysis

To investigate whether there is a threshold effect between the digital economy and carbon emission intensity. In this paper, ln*TRE*, ln*LRE* and ln*CRE* were used as threshold variables to test the threshold effect by bootstrap method. As can be seen from Table 7, both technical resource endowment (ln*TRE*) and labor resource endowment (ln*LRE*) pass the double threshold test, while economic development level (ln*PGDP*) passes the single threshold test, the Fig. 9 is their Plot of threshold effect likelihood ratio function.

The regression results of threshold effect in Table 8 show the impact of digital economy on carbon emission intensity under different threshold values. Obviously, when

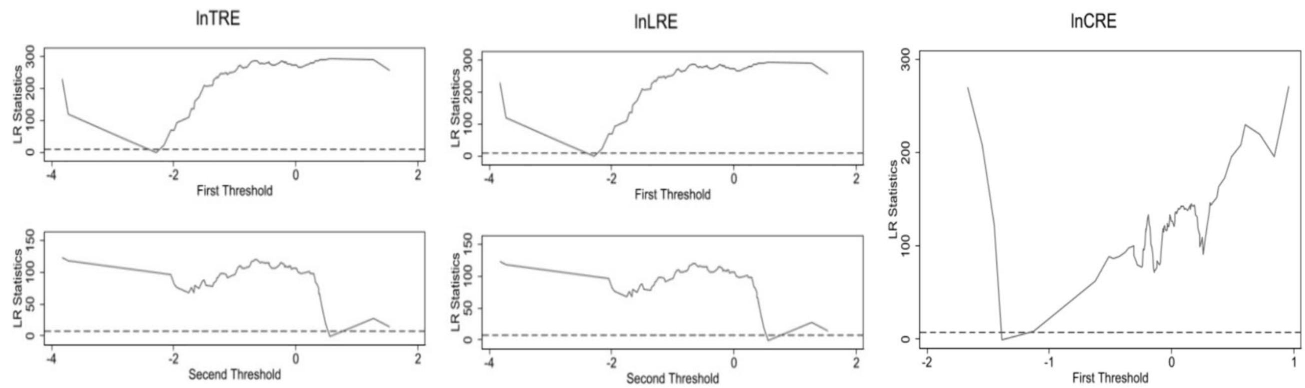

Fig. 9 Plot of threshold effect likelihood ratio function

Table 8 The results of threshold effect analysis

Variable	ln*CEI*		
	M1	M2	M3
ln*DE*	0.869***(ln*TRE* < = – 2.286) (0.000)	1.072***(ln*LRE* < = – 1.466) (0.000)	1.059***(ln*CRE* < = – 1.387) (0.000)
	– 0.221*(0.553 > = ln*TRE* > – 2.286) (0.082)	0.193*(– 0.171 > = ln*LRE* > – 1.466) (0.077)	– 0.207(ln*CRE* > – 1.387) (0.116)
	– 1.023***(ln*TRE* > 0.553) (0.001)	– 1.77**(ln*LRE* > – 0.171) (0.049)	
Constant	20.730*** (0.000)	24.519*** (0.000)	22.821*** (0.000)
Control	Yes	Yes	Yes
R^2	0.727	0.797	0.680
Obs	330	330	330

Notes: *, **, and *** represent the significance at 10%, 5%, and 1% levels, respectively

the technology factor is lower than the threshold value -2.286, the digital economy has a significant promotion effect on carbon emission intensity, while when the technology factor is higher than the threshold value − 2.286, the digital economy has a significant inhibition effect on carbon emission intensity. Moreover, compared with ln*TRE* between − 2.286 and 0.533, when ln*TRE* is higher than 0.553, the inhibition effect of digital economy on carbon emission intensity is stronger. The reason is that the low level of technical elements means that the energy efficiency of existing technologies may not be high, and digital economic activities may not be able to effectively reduce energy consumption and carbon emissions in the absence of technical support from universities. At the same time, in the case of insufficient technical elements, the digital economy has limited substitution effect on traditional high-carbon emission activities. More importantly, when the technical elements are low, it is the early stage of the construction of the digital economy, at which time more infrastructure needs to be invested to develop the digital economy, and a large amount of carbon emissions will be generated in the construction process. In the short term, the carbon emission reduction effect brought by the digital economy will not fully offset the carbon emissions generated, so carbon emissions will increase. In the case of a higher level of technical elements, technological progress can improve energy efficiency, the substitution effect will be enhanced, and the industrial structure will be optimized, so carbon emissions will be reduced. Similar to the technical factors, when the labor factor level is lower than the threshold value − 0.171, the digital economy has a significantly positive impact on carbon emission intensity, while when it is higher than the threshold value − 0.171, the digital economy has a significantly negative impact on carbon emission intensity. To explore the reasons from an economic perspective, the labor force is an important factor input for economic development. For regions with a high level of labor force, relying on a large number of low-cost labor force to attract a lot of overseas investment, relying on the advantages of labor resources, alliance with overseas investors to develop labor-intensive industries, learn from their advanced technical experience, and promote technological progress to reduce carbon emissions. Another situation appears in Table 8. When capital endowment level is low, the digital economy has a significantly positive impact on carbon emission intensity, while when capital endowment level is high, the digital economy has a negative but insignificant impact on carbon emission intensity. This situation can be explained by the fact that in an environment with limited capital, the digital economy has a significant impact on carbon emission intensity. Enterprises may be more inclined to adopt cost-priced but inefficient technologies, which directly leads to digital economic activities in the energy efficiency of the capital is not as good as in the capital shortage area, often in the capital shortage area, the local government or enterprises pay more attention to economic development and ignore the digital economy on carbon emission intensity.

Heterogeneity Analysis

Regional Heterogeneity Analysis

Due to the different development levels and factor endowments of each province, this paper divides China into four regions: the eastern region, the central region, the western region, and the northeastern region, and then analyzes whether there are regional differences in the impact of each region's digital economy level on carbon emission intensity, as shown in Table 9.

Based on the spatial Durbin model to analyze the impact of the level of digital economy on carbon emission intensity in each region, the specific regression results are shown in Table 10. As can be seen from the results of Table 10 (1–4), the digital economy in the eastern and central regions will significantly promote carbon emission intensity, while the digital economy in the western and northeastern regions will significantly promote carbon emission intensity. This is because the economy in the eastern and central regions is more developed, the process of urbanization is fast, the population is dense, and the consumer demand is strong. The rapid development of the digital economy, especially the extensive application of information technology such as the Internet, big data and cloud computing, has promoted the transformation of consumption patterns, and these activities may increase carbon emission intensity in the short term due to the construction of infrastructure and the increased

Table 9 The regional division

Regional division	Provinces and cities
Eastern	Beijing; Tianjin; Hebei; Shandong; Jiangsu; Shanghai; Zhejiang; Fujian; Guangdong; Hainan
Middle	Shanxi; Henan; Anhui; Hubei; Jiangxi; Hunan
Western	Shanxi; Sichuan; Chongqing; Yunnan; Guizhou; Guangxi; Gansu; Qinghai; Ningxia; Xinjiang; Inner Mongolia
Northeastern	Heilongjiang; Jilin; Liaoning

Table 10 Regional Heterogeneity Analysis

	(1) Eastern	(2) Middle	(3) Western	(4) Northeastern	(5) Positive reduction region	(6) Passive reduction region
x						
ln*DE*	0.112** (0.032)	0.629** (0.038)	– 0.117*** (0.009)	– 0.461*** (0.000)	0.263*** (0.000)	– 0.150*** (0.000)
W.x						
ln*DE*	0.245 (0.172)	1.445* (0.101)	0.002 (0.996)	– 0.308** (0.024)	0.422 (0.161)	– 0.088 (0.695)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Double fixed	Yes	Yes	Yes	Yes	Yes	Yes

Notes: *, **, and *** represent the significance at 10%, 5%, and 1% levels, respectively

Table 11 Classification table of differences in local government behavior

Classification	Division into provinces and cities
Active carbon reduction areas	Beijing; Shanghai; Guangdong; Jiangsu; Zhejiang; Shandong; Tianjin; Fujian; Guangxi; Hainan; Jiangxi
More passive carbon reduction areas	Inner Mongolia; Heilongjiang; Liaoning; Jilin; Hebei; Henan; Chongqing; Shaanxi; Sichuan; Guizhou; Yunnan; Anhui; Hubei; Hunan; Shanxi; Qinghai; Xinjiang; Gansu; Ningxia

use of equipment. Although the western and northeastern regions have a small economic aggregate, they are rich in resources, especially fossil energy reserves such as coal and oil. The development of the digital economy in these regions is more reflected in the intelligence of resource extraction and processing, which can improve energy efficiency and reduce waste, thus curbing carbon emission intensity.

Different local governments have different policy orientations and administrative capabilities. Some local governments may pay more attention to environmental protection and carbon emission reduction, while others may be more passive in this regard. Therefore, this paper takes into account the impact of local government behaviors on digital economy and carbon emission reduction, and divides them into regions that actively promote carbon emission reduction and regions that are more passive. This division is mainly based on the local government's environmental protection policies and the implementation of carbon emission reduction measures, specifically in terms of environmental policy formulation and implementation, carbon emission data disclosure and supervision, carbon emission reduction projects and investment support, carbon market construction and policy support. The specific divisions are as follows Table 11.

From columns 5 and 6 in the Table 10, digital economy in regions with active emission reduction significantly promotes carbon emission intensity, while the digital economy in regions with negative emission reduction significantly inhibits carbon emission intensity. This seemingly contradictory situation is actually related to regional differences. Regions that actively reduce emissions may be trying to adopt the latest and most efficient technologies to reduce carbon emissions, but this is usually accompanied by high initial investment and operating costs, which in the short term will be reflected in rising carbon intensity costs, and the development of the digital economy requires a lot of infrastructure construction, which will generate a lot of energy in the construction process. It will also increase carbon emissions in the short term, but the performance will be positive in the long term. In regions with negative emission reduction, the development of the digital economy may accelerate the transition from high-carbon emission industries to low-carbon industries, while the development of the digital economy may replace high-carbon emission economic activities, thereby reducing carbon emissions. The positive emission reduction areas were in the eastern and central regions, while the negative emission reduction areas were basically in the western and northeastern regions, and the results proved to be the same in both cases.

Elemental Heterogeneity Analysis

According to factor endowment theory, the relationship between factor endowment and industrial structure according to factor endowment structure development of industry has comparative advantage, the production of products with comparative advantage is also the most competitive, the profit rate obtained will be the highest, the faster the accumulation of capital. The article analyzes the

Table 12 Elemental Heterogeneity Analysis

	(1) Abundant capital	(2) Lack of capital	(3) Abundant labor	(4) Lack of labor	(5) Abundant technical	(6) Lack of technical
x						
ln*DE*	– 0.188***	– 0.124***	– 0.141***	– 0.191***	– 0.302	– 0.071**
	(0.004)	(0.000)	(0.007)	(0.000)	(0.147)	(0.046)
W.x						
ln*DE*	– 0.791*	– 0.213	0.064	1.598***	– 1.927	– 0.106
	(0.082)	(0.183)	(0.835)	(0.004)	(0106)	(0.633)
Control variable	Yes	Yes	Yes	Yes	Yes	Yes
Double fixed	Yes	Yes	Yes	Yes	Yes	Yes

Notes: *, **, and *** represent the significance at 10%, 5%, and 1% levels, respectively

impact of digital economy development level on carbon emission intensity under different factor endowments from three production factors: labor, technology and capital. The resource endowment coefficient is used to indicate the relative abundance or scarcity of resource endowment. If the resource endowment coefficient is greater than 1, it indicates that the factor is relatively abundant; if the resource endowment coefficient is less than 1, it indicates that the factor is relatively scarce.

(1) Capital endowment. In columns 1–2 of Table 12, the results show that the digital economy has a significant suppressive effect on carbon emission intensity in both regions with abundant and scarce capital factors. However, the inhibitory effect of digital economy development level on carbon emission intensity is stronger and more significant in regions with abundant capital factors compared to regions with scarce capital factors. This is because the capital factor can provide a good economic foundation for the development of digital economy. At the same time, it can be seen that there is a spatial spillover effect of the digital economy on carbon emission intensity in regions with abundant capital factors, and it can significantly suppress the carbon emission intensity in the surrounding areas, but there is no spatial spillover effect of the digital economy on carbon emission intensity in regions with scarce capital factors. This may be due to the fact that in regions with abundant capital factors, the development of digital economy is faster and can radiate the development of digital economy in neighboring regions, which can influence the impact of digital economy on carbon emission intensity in neighboring regions.

(2) Labor Endowment. In columns 3–4 of Table 12, this result shows that the digital economy has a significant inhibitory effect on carbon emission intensity in both the case of labor scarcity and abundance. The reason is that in areas lacking labor factors, enterprises are often more inclined to adopt automation and intelligent technology to make up for the shortage of labor force, which not only improves production efficiency, but also reduces the dependence on manpower, which is often accompanied by more efficient energy use and lower carbon emissions. In labor-rich regions, the digital economy can reduce carbon emissions per unit of output by increasing labor productivity. At the same time, the spread of digital technologies can also encourage more people to participate in high-skilled, low-emission jobs, further reducing carbon intensity. So whether labor is abundant or lacking, the digital economy can reduce carbon intensity.

(3) Technology Endowment. In columns 5–6 of Table 12, we can see that in areas with abundant technology, the digital economy has no significant impact on carbon emission intensity, but in areas with limited technology, the digital economy has a more significant inhibitory effect on carbon emission intensity, the reason is that in an environment with abundant technological elements, new technologies and innovations are often easier to spread and adopt, and digital economy-related technologies have been widely used in many industries and fields, which means that these technologies may have reached a higher maturity and effect, and the marginal effect has begun to decline. In other words, with the continuous application of technology, its effect on reducing carbon emissions gradually becomes stable, so there may be a statistically insignificant impact. In areas where technology is scarce, the spread of the digital economy can initiate a series of substitution effects, such as the substitution of digital services for physical services, which will have a particularly significant impact on carbon intensity in the initial stage, because they directly reduce activities with high carbon emissions. As stated by Yu et al. (2022), digital technology is the core foundation for the development of digital economy, and the development of digital technology will cause a large amount of energy consumption, which will increase carbon emissions.

Robustness Test

To ensure the accuracy of the regression results, a series of robustness tests were conducted in this paper, and the results are shown in Table 13.

(1) Substitution of explanatory variables. In this paper, carbon emission level is used instead of carbon emission intensity to test the robustness, and Model 1 of Table 13 shows that the digital economy level can significantly reduce the carbon emission level. It is consistent with the conclusion obtained in the previous paper, so it is robust.

(2) Change the spatial weight matrix. The inverse distance weight matrix used in the previous spatial Durbin model was changed to the adjacency matrix and the economic weight matrix to test its robustness. Model 2 of Table 13 both indicate a significant negative effect between the level of digital economy and carbon emission intensity. The pre and post results are consistent, so the results are robust.

Table 13 The results of robustness test

Variable	(1) Substitution of explanatory variables		(2) Change the spatial weight matrix				(3) Removal of municipalities	
	ln*CE*		Adjacency matrix		Economic weighting matrix		ln*CEI*	
	X	W.x	X	W.x	X	W.x	X	W.x
ln*DE*	– 0.127***	– 0.124	– 0.100***	0.103	– 0.114***	0.067	– 0.053*	0.247
	(0.000)	(0.556)	(0.000)	(0.837)	(0.000)	(0.198)	(0.073)	(0.273)
ln*FDI*	– 0.000	0.074	0.004	0.021	0.011	– 0.020	– 0.020*	– 0.256***
	(0.976)	(0.291)	(0.701)	(0.918)	(0.245)	(0.245)	(0.062)	(0.001)
ln*UL*	– 0.084	– 0.480	– 0.063	0.377	– 0.154**	– 0.034	0.150**	0.611
	(0.267)	(0.266)	(0.613)	(0.690)	(0.028)	(0.751)	(0.037)	(0.223)
ln*TO*	1.172***	0.628	0.585**	– 1.217	0.682***	0.118	0.790***	3.603*
	(0.000)	(0.679)	(0.011)	(0.470)	(0.000)	(0.667)	(0.004)	(0.0896)
ln*ERA*	– 0.065***	– 0.120	– 0.057	0.039	– 0.024	0.089**	0.054**	0.825***
	(0.002)	(0.465)	(0.189)	(0.877)	(0.282)	(0.011)	(0.024)	(0.000)
ln*ERB*	0.011	– 0.029	0.014	– 0.002	0.010	0.022**	0.023**	0.143**
	(0.156)	(0.585)	(0.241)	(0.990)	(0.205)	(0.032)	(0.012)	(0.030)
ln*ERC*	– 0.002	– 0.005	– 0.002	– 0.004	– 0.002*	0.001	– 0.001	0.004
	(0.207)	(0.657)	(0.216)	(0.798)	(0.068)	(0.532)	(0.577)	(0.741)
ln*LRE*	– 0.014***	0.037	– 0.012**	0.005	– 0.010**	– 0.012	– 0.003	0.009
	(0.007)	(0.340)	(0.026)	(0.917)	(0.039)	(0.104)	(0.591)	(0.7873)
ln*TRE*	0.172**	0.415	0.992***	0.075	0.930***	0.445***	1.054***	0.359
	(0.042)	(0.506)	(0.000)	(0.944)	(0.000)	(0.002)	(0.000)	(0.657)
ln*CRE*	0.121***	0.443	0.105	– 0.029	0.147***	0.082	– 0.034	0.248
	(0.009)	(0.183)	(0.129)	(0.922)	(0.001)	(0.313)	(0.324)	(0.3301)
ln*Pop*	– 0.324***	– 0.792	– 0.124	0.153	– 0.103	– 0.321**	– 0.066	– 1.810
	(0.000)	(0.213)	(0.111)	(0.931)	(0.176)	(0.040)	(0.887)	(0.551)
ln*Trans*	0.540***	2.298**	– 0.385*	1.292	– 0.559***	– 0.221	0.085	– 3.606***
	(0.001)	(0.017)	(0.070)	(0.264)	(0.000)	(0.383)	(0.407)	(0.000)
ln*CS*	0.330***	0.503	0.278**	0.064	0.376***	0.053	– 0.031	– 1.543*
	(0.001)	(0.584)	(0.038)	(0.935)	(0.000)	(0.728)	(0.889)	(0.074)
ln*RD*	– 0.330**	– 3.919***	– 0.349**	– 0.690	– 0.462***	– 0.690***	– 0.340***	6.120***
	(0.022)	(0.000)	(0.043)	(0.671)	(0.001)	(0.006)	(0.000)	(0.0015)
ln*NR*	– 0.213***	– 0.635*	– 0.197***	– 0.602*	– 0.205***	– 0.017	0.012	0.455
	(0.000)	(0.053)	(0.000)	(0.062)	(0.000)	(0.800)	(0.8392)	(0.368)
Lcpc	– 0.154**	0.314	– 0.174**	0.307	– 0.150**	– 0.099	0.031	– 0.020
	(0.012)	(0.564)	(0.015)	(0.493)	(0.015)	(0.358)	(0.1050)	(0.891)
N	330		330		330		286	

Notes: *, **, and *** represent the significance at 10%, 5%, and 1% levels, respectively

(3) Removal of municipalities. Considering that municipalities directly administered by the government are significantly different from other cities, four municipalities, namely Beijing, Tianjin, Shanghai, and Chongqing, are removed from this paper. Model 3 of Table 13 shows that after removing the municipalities directly under the central government, the relationship between the level of digital economy and carbon emission intensity is still significantly negative, which is consistent with the previous results and is therefore robust.

Table 14 Endogeneity test

Variable	(1) ln*DE*	(2) ln*CEI*	(3) ln*DE*	(4) ln*CEI*
ln*DE*		– 0.135** (0.004)		– 0.124** (0.020)
IV	0.298*** (0.000)	0.080* (0.082)		
ln*DE_lag*			0.503*** (0.000)	– 0.033 (0.529)
W*ln*DE*	2.041** (0.020)		20.235 (0.006)	
Control variable	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Province	Yes	Yes	Yes	Yes
N	270	270	240	240
R^2	0.8273	0.541	0.575	0.550
F Statistics	348.923*** (0.000)	58.608*** (0.000)	10.042*** (0.000)	416.806*** (0.000)

Notes: *, **, and *** represent the significance at 10%, 5%, and 1% levels, respectively

Endogeneity Test

It is likely that the impact of the digital economy on carbon emission intensity will also be affected by other factors not taken into account, as well as endogeneity due to the reverse causality that exists between carbon emission intensity and the digital economy. Therefore, we apply the instrumental variable method to test for endogeneity. Referring to the idea of Zhang et al. (2023b), this paper chooses the number of Internet broadband access subscribers in the previous year and the number of fixed-line telephones per 100 people in 1984 as the first instrumental variables of the digital economy in order to mitigate the effect of omitted variables. Meanwhile, the lagged one-period data of the digital economy is chosen as the second instrumental variable to mitigate the endogeneity caused by reverse causality and tested by the estimation method of generalized spatial two-stage least squares (GS2SLS) (Wang and Guo 2023). The first and third columns of Table 14 indicate that the selected instrumental variables pass the weak instrumental variables test. The results in columns 2 and 4 are consistent with the benchmark regression results, further demonstrating the robustness of the benchmark results.

Conclusions and Policy Implications

Conclusions

With the rapid development of the Internet, the development of digital economy has also received wide attention from government departments. At present, more and more scholars apply the digital economy to the carbon emission reduction path, and this paper also explores the impact and mechanism of the digital economy on carbon emission intensity. This paper uses panel data of 30 Chinese provinces from 2011 to 2021 to verify how the digital economy affects carbon emission intensity. This paper constructs a spatial Durbin model, a mediating effect model and a threshold effect model to test the impact and mechanism of the level of digital economy on carbon emission intensity from several aspects, and also to test whether there is a threshold effect on the impact of digital economy on carbon emission intensity. The main findings are as follows:

First of all, the development level of digital economy has a significant negative effect on carbon emission reduction. Further tests of the mediating mechanism show that industrial structure, energy consumption structure, green technology innovation and resource allocation efficiency have mediating effects on the impact of digital economy on carbon emission intensity. Specifically, the digital economy can reduce carbon intensity by optimizing the industrial structure, promoting the transformation of the energy structure, improving green technology innovation, and optimizing the allocation of resources.

Second, the digital economy has a threshold effect on carbon emission intensity, with lnTRE and lnLRE passing the double threshold test and lnPGDP passing the single threshold test.

- For the dual threshold effect of lnTRE, the corresponding thresholds are – 2.286 and 0.553 respectively. When lnTRE is lower than the threshold of – 2.286, the digital economy has a significant promotion effect on carbon emission intensity, while when lnTRE is higher than the threshold of – 2.286, the digital economy has a significant inhibition effect on carbon emission intensity.
- For the dual threshold effects of lnLRE, the corresponding thresholds are – 1.466 and – 0.171 respectively. When the level of labor factors is lower than the threshold value of – 0.171, the digital economy has a significant positive impact on carbon emission intensity, while when the level of labor factors is higher than the threshold value of – 0.171, the digital economy has a significant negative impact on carbon emission intensity.
- For the single threshold effect of lnPGDP, the corresponding threshold value is – 1.387. When lnPGDP is lower than the threshold value – 1.387, the digital economy has a significant positive impact on carbon emission intensity, while when lnPGDP is higher than the threshold value – 1.387, the digital economy has a non-significant negative impact on carbon emission intensity.

Third, we also further analyze the heterogeneity of this effect.

- The regional heterogeneity test shows that the digital economy in the eastern region has a significant impact on carbon emission intensity. For the central and western regions, the digital economy level has a positive impact on carbon emission intensity, but the promotion effect of the western region is not significant.
- The factor endowment heterogeneity test shows that digital economy has a significant inhibitory effect on carbon emission intensity in both regions with abundant capital factor endowments and regions with scarce capital factor endowments, but the inhibitory effect is more intense in regions with abundant capital factors. In areas with abundant technological elements, the development of digital economy has no significant effect on reducing carbon emission intensity, but in areas lacking technological elements, digital economy can significantly reduce carbon emission intensity.

Policy Implications

Based on the research in this paper, the authors make the following policy recommendations:

1. The government and enterprises should increase the scale of digital economy, continue to improve the construction of digital economy infrastructure, and enhance digital innovation. This study shows that the digital economy can significantly reduce carbon emission intensity and has significant spatial spillover effects. On the one hand, governments and enterprises should focus on developing the digital economy, integrating digital industries with traditional industries, promoting the research, development and utilization of green technologies, and improving the operational efficiency and energy utilization efficiency of various industry sectors. On the other hand, the development of regional digital economy synergy should be accelerated to give full play to the spillover of digital economy on reducing carbon emission intensity. However, attention should also be paid to the development model of the digital economy, which can also have adverse effects on the environment if it only aims to expand in scale and ignores environmental issues. Therefore, the development of digital economy should also follow the principle of sustainable development.
2. We will strengthen the coordinated development of the digital economy across regions and bridge the "digital divide". In view of the trans-regional spillover effects that digital economy development may produce, the research also shows that there are significant differences in the level of digital economy development and carbon emission intensity in different regions. For example, the article shows that the digitalization level of the eastern region is much higher than the digital economy development level of the central and western regions, so the state and the government should establish a cooperation mechanism, coordinate relevant policies, avoid duplication of construction, and consider the digital infrastructure construction of the central and western regions while vigorously developing the digital economy level of the eastern region. The government should take into account the actual situation of the region and reasonably formulate relevant measures in line with local conditions to avoid resource loss. At the same time, we should strengthen international exchanges and cooperation, learn from the experience of other countries, and promote global green transformation.
3. Optimize the industrial structure and promote the transformation of energy structure. With the rapid development of digital economy, Internet industry, e-commerce industry and communication industry can crowd out high energy-consuming industries, and digital economy can promote the development of green and intelligent industrial chain and optimize industrial structure. Research shows that the development of digital economy can promote the transformation of industrial structure to tertiary industry, gradually eliminate old industries with high energy consumption and carbon emission, and improve the production technology and management mode of industries, and the upgrading of industrial structure is conducive to the reduction of total carbon emission. Therefore, the government should encourage enterprises to combine digital industries with traditional industries to realize the upgrading and optimization of industrial structure, and to create and cultivate new industrial models. At the same time, the government should encourage the development and utilization of clean energy, reduce the dependence on fossil energy, and transform toward new clean energy.
4. Strengthen the construction of talent support, and actively implement the strategy of science and education. Technology is the first productive force, talent is the first resource, and innovation is the first driving force. Technological innovation and talent training, as two important pillars of modern economic development, are the key to achieving sustainable economic and social development. In modern society, talents have become the most important productive force, and more talent capital is created for society through education and training. High-quality talents have stronger environmental awareness and responsibility for environmental protection, while the advanced talent capital helps

society to carry out more environmental technology innovation activities. Technological innovation helps people to use resources more efficiently and can promote the development of a green economy. However, it is also important to focus on environmental protection and sustainable development in the process of technological innovation to avoid a situation where innovation has a negative impact on the environment.

Discussion

The development of the digital economy can effectively mitigate carbon emissions, as evidenced by various relevant studies (Wu et al. 2024; Hong et al. 2024). On one hand, the digital economy enhances energy efficiency. For instance, smart grids optimize electricity distribution and minimize waste, while smart home systems adjust energy consumption based on occupants' actual needs. Furthermore, Industry 4.0's smart factories utilize digital technology to automate production processes and reduce energy waste and carbon emissions. On the other hand, the digital economy promotes resource recycling through platforms such as second-hand markets and sharing economies, thereby reducing demand for new resources and lowering carbon emissions in production processes. Intelligent building management systems also contribute to reduced energy consumption through automated control and data analysis. Consequently, the development of the digital economy can help individuals break free from traditional energy-intensive lifestyles. In summary, the digital economy reduces carbon emissions by enhancing energy efficiency and resource utilization. This indicates a mediating effect in its relationship with carbon emissions. The findings of this study align with those of Li et al. (2024), both demonstrating that technological innovation and industrial structure play intermediary roles between the digital economy and carbon emissions. Regarding this paper's threshold effect test, an intriguing phenomenon is observed: The level of digital economic development serves as a threshold variable with a specific value; thus dividing the regression relationship between the digital economy and carbon emission intensity into two intervals. In regions with low levels of digital economic development, it significantly inhibits carbon emission intensity; conversely in regions with higher levels of development, it has a promoting effect on emission intensity but not significantly so. This may be attributed to extensive growth leading to higher levels of digitization but increased energy consumption offsetting initial positive impacts—resulting in insignificant effects on reducing carbon emission intensity.

Research Gaps and Outlook

Since the data of digital economy often need to be collected from different fields, and these data are difficult to obtain, resulting in incomplete data, and the indicator system chosen in the part of measuring the level of digital economy is not perfect, which may lead to some bias in the final results. When studying the impact of digital economy on carbon emissions in the future, more attention should be paid to the relationship between individual behavior and carbon emissions. The deficiency in data can be improved by building a comprehensive data sharing platform through technical means to improve data access. The digital economy can be used as a driving force for environmental protection and energy transformation, and governments and companies can use digital means to develop more green technologies that can be applied in practice. Perhaps in the future, interdisciplinary research can also be conducted to integrate the knowledge of multiple disciplines such as economics, environmental science, and information technology, and adopt an interdisciplinary approach to study the relationship between digital economy and the environment. For example, combining the theory of system dynamics and ecological economics, the feedback mechanism of complex systems is discussed. The research perspective can be expanded to a global perspective and international cooperation, examining the interaction between the digital economy and carbon emissions on a global scale, and studying how to promote the realization of global carbon emission reduction targets through international cooperation mechanisms, especially in the technology transfer between developed and developing countries.

Author Contributions Conceptualization, Methodology, Writing – review & editing, Formal analysis, Funding acquisition, Chuang Li; Data curation, Resources, Writing – original draft, Formal analysis, Validation, Qin Zhao; Formal analysis, Supervision, Writing – review & editing, Project administration, Liping Wang.

Funding National Social Science Fund of China, 23FJYB029, Chuang Li, Innovation Strategy Research Plan Project of Fujian Province, 2023R0050, Chuang Li, Social Science Fund of Fujian Province, FJ2024A005, Liping Wang

Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare that there is no conflict of interests.

Ethical Approval This study conforms to the ethical and moral requirements.

Consent to Participate All the authors of this article were consented to participate.

Consent to Publish This study was consented to be published.

References

Abrell J, Kosch M, Rausch S (2022) How effective is carbon pricing?—a machine learning approach to policy evaluation. J Environ Econ Manag 112:102589

Ahmadova G, Delgado-Márquez BL, Pedauga LE et al (2022) Too good to be true: the inverted U-shaped relationship between Home-Country digitalization and environmental performance. Ecol Econ 196:107393

Ahmed F, Naeem M, Iqbal M (2016) ICT and renewable energy: a way forward to the next generation telecom base stations. Telecommun Syst 64(1):43–56

Ahmed Z, Asghar MM, Malik MN et al (2020) Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. Resour Policy 67:101677

Amri F, Zaied YB, Lahouel BB (2019) ICT, total factor productivity, and carbon dioxide emissions in Tunisia. Technol Forecast Soc 146:212–217

Azam A, Rafiq M, Shafique M et al (2021) An empirical analysis of the non-linear effects of natural gas, nuclear energy, renewable energy and ICT-Trade in leading CO_2 emitter countries: policy towards CO_2 mitigation and economic sustainability. J Environ Manage 286:112232

Bai JH, Liu YY (2018) Can Outward foreign direct investment improve the resource misallocation of China. China Industrial Econ 1:60–78

Bai CQ, Chen ZJ, Wang DP (2023) Transportation carbon emission reduction potential and mitigation strategy in China. Sci Total Environ 873:162074

Bughin J, Kretschmer T, Van Zeebroeck N (2021) Digital technology adoption drives strategic renewal for successful digital transformation. IEEE Eng Manage Rev 49(3):103–108

Çakar ND, Gedikli A, Erdoğan S et al (2021) Exploring the nexus between human capital and environmental degradation: the case of EU countries. J Environ Manage 295:113057

Chen PY (2022) Is the digital economy driving clean energy development? —new evidence from 276 cities in China. J Clean Prod 372:133783

Chen FZ, Jiang GH, Dong KY (2024) Spatial spillover effects of the digital economy on the green transformation of the manufacturing industry. Chin J Popul Res Environ 34(5):114–125

Chishti MZ, Sinha A, Zaman U et al (2023) Exploring the dynamic connectedness among energy transition and its drivers: understanding the moderating role of global geopolitical risk. Energ Econ 119:106570

Deng H, Li C, Wang LP (2022) The impact of corporate innovation on environmental performance: the moderating effect of financing constraints and government subsidies. Sustainability 14:11530

Ding ZL (2021) The key to achieving carbon neutrality is to build a "Three-Terminal Force" System". China Petrol Enterp 6:10–11+111

Dong F, Hu M, Gao YJ et al (2022) How does digital economy affect carbon emissions? Evidence from global 60 countries. Sci Total Environ 852:158401

Fan D, Sun XT (2020) Environmental regulation, green technological innovation and green economic growth. Chin J Popul Resour Environ 30(6):105–115

Fang GC, Yang K, Tian LX et al (2022) Can environmental tax promote renewable energy consumption? — an empirical study from the typical countries along the Belt and Road. Energy 260:125193

Ge WF, Xu Y, Liu GL et al (2022) Exploring the impact of the digital economy on carbon emission efficiency under factor misallocation constraints: new insights from China". Front Env Sci 10:1–16

Goulder LH, Long XL, Lu J et al (2022) China's unconventional nationwide CO_2 emissions trading system: cost-effectiveness and distributional impacts. J Environ Econ Manage 111:102561

Gowd SC, Ganeshan P, Vigneswaran VS et al (2023) Economic perspectives and policy insights on carbon capture, storage, and utilization for sustainable development. Sci Total Environ 883:163656

Guan YR, Shan YL, Huang Q et al (2021) Assessment to China's recent emission pattern shifts. Earth's Future 9(11):e2021EF002241

Guo F, Wang JY, Wang F et al (2020) Measuring China's digital financial inclusion: index compilation spatial characteristics. Economics 19(04):1401–1418

Guo YL, Jia JS, Li L et al (2024) Spatio-temporal pattern and influencing factors of carbon emissions in the middle reaches of the Yellow River from the perspective of urban shrinkage. Acta Ecol Sin 44(03):903–914

Guo AJ, Zhang CB (2023) How does the digital economy affect the intensity of carbon emissions-Based on the dual perspectives of industrial structure upgrading and rationalization. Sci manag sci technol 1–28

Hao Y, Gai Z, Wu H (2020) How do resource misallocation and government corruption affect green total factor energy efficiency? Evidence from China. Energ Policy 143:111562

Hao XL, Li YH, Ren SY et al (2023) The role of digitalization on green economic growth: does industrial structure optimization and green innovation matter? J Environ Manage 325:116504

Hong SF, Hui ECM, Lin YY (2022) Relationships between carbon emissions and urban population size and density, based on geo-urban scaling analysis: a multi-carbon source empirical study. Urban Clim 46:101337

Hong JK, Huang H, Wang XZ et al (2024) Structural effects of provincial digital economy on carbon emissions within China: a multi-region input-output based structural decomposition analysis. Sci Total Environ 934:173140

Huo P, Wang LX (2022) Digital economy and business investment efficiency: inhibiting or facilitating? Res Int Bus Financ 63:101797

Jiang W, Sun YF (2023) Which is the more important factor of carbon emission, coal consumption or industrial structure? Energ Policy 176:113508

Kretschmer T, Khashabi P (2020) Digital transformation and organization design: an integrated approach. Calif Manage Rev 62(4):86–104

Li ZG, Wang J (2022a) The dynamic impact of digital economy on carbon emission reduction: evidence city-level empirical data in China. J Clean Prod 351:131570

Li MN, Zhou YB (2022b) Research on human capital structure effect of digital economy development. Resour Econ Manag 43(1):23–38

Li CY, Zhou WS (2024) Can digital economy development contribute to urban carbon emission reduction? – Empirical evidence from China. J Environ Manage 357:120680

Li L, McMurray A, Li XM et al (2021) The diminishing marginal effect of R&D input and carbon emission mitigation. J Clean Prod 282:124423

Li RR, Li LJ, Wang Q (2022c) The impact of energy efficiency on carbon emissions: evidence from the transportation sector in Chinese 30 provinces. Sustain Cities Soc 82:103880

Li C, Xia W, Wang L (2023a) Synergies of green policies and their pollution reduction effects: quantitative analysis of China's green policy texts. J Clean Prod 412:137360

Li C, Zhang Z, Wang L (2023b) Carbon peak forecast and low carbon policy choice of transportation industry in China: scenario prediction based on STIRPAT model. Environ Sci Pollut R 30(22):63250–63271
Liao ZJ, Zhang JY, Chen SW (2023) Research on carbon emission influencing factors and carbon peak reaching pathways-evidence from Sichuan province. Soft Sci 37(09):95–101
Lin BQ, Ge JM (2019) Valued forest carbon sinks: How much emissions abatement costs could be reduced in China. J Clean Prod 224:455–464
Lin BQ, Ma RY (2022) How does digital finance influence green technology innovation in China? Evidence from the financing constraints perspective. J Environ Manage 320:115833
Liu JH, Zhou K, Zhang Y et al (2022) Digital inclusive finance, enterprise life cycle and technological innovation. Stat Decis 38(19):130–134
Lyu YW, Wang WQ, Wu Y et al (2023) How does digital economy affect green total factor productivity? Evidence from China. Sci Total Environ 857:159428
Ouyang XL, Zhang JH, Du G (2022) Environmental regulation and green technological innovation: impact mechanism analysis and spatial spillover effects. Chin J Manag Sci 30(12):141–151
Ozturk I, Ullah S (2022) Does digital financial inclusion matter for economic growth and environmental sustainability in OBRI economies? An empirical analysis. Resour Conserv Recy 185:106489
Pan WR, Xie T, Wang ZW et al (2022) Digital economy: an innovation driver for total factor productivity. J Bus Res 139(169):303–311
Qu SN, Shi D, Yang DH (2022) Carbon emissions of China's digital economy: calculations and trend outlook. Chin J Popul Res Environ 32(9):11–21
Ren SY, Hao Y, Xu L et al (2021) Digitalization and energy: how does internet development affect China's energy consumption? Energ Econ 98:105220
Shahbaz M, Wang JD, Dong KY et al (2022) The impact of digital economy on energy transition across the globe: the mediating role of government governance. Renew Sust Energ Rev 166:112620
Shan HJ (2008) Reestimating the capital stock of China:1952–2006. J Quant Tech Econ 25(10):17–31
Shan YL, Liu JH, Liu Z et al (2016) New provincial CO2 emission inventories in China based on apparent energy consumption data and updated emission factors. Appl Energ 184:742–750
Shan et al (2018) China CO2 emission accounts 1997–2015. Sci Data 5:170201
Shan et al (2020) China CO2 emission accounts 2016–2017. Sci Data 7(1):54
Shi D (2022) Evolution of industrial development trend under digital economy. China Industrial Econ 11:26–42
Shi DQ, Ding H (2018) Can smart city construction reduce environmental pollution. China Industrial Econ 6:117–135
Skare M, de Obesso MDLM, Ribeiro-Navarrete S (2023) Digital transformation and European small and medium enterprises (SMEs): A comparative study using digital economy and society index data. Int J Inf Manage 68:102594
Song ML, Wang SH, Zhang HY (2020) Could environmental regulation and R&D tax incentives affect green product innovation. J Clean Prod 258:120849
Su X, Tan JL (2023) Regional energy transition path and the role of government support and resource endowment in China. Renew Sust Energ Rev 174:113150
Su JQ, Su K, Wang SB (2021) Does the digital economy promote industrial structural upgrading?—a test of mediating effects based on heterogeneous technological innovation. Sustainability 13(18):10105
Tang J, Li YT, Gao Y (2024) Spatial effects of energy system digitization on carbon emissions: evidence from China. Sustainability 16(5):1822
Teng Y, Zheng YH (2023) Research on the impact of digitalization of manufacturing enterprises on corporate carbon emissions-A reexamination of the 'Jevons Paradox' from a micro perspective. J Ind Technol Econ 42:48–56
Villanthenkodath MA, Ansari MA, Kumar P et al (2022) Effect of information and communication technology on the environmental sustainability: an empirical assessment for South Africa. Telemat Inform Rep 7:100013
Wang J, Guo D (2023) Siphon and radiation effects of ICT agglomeration on green total factor productivity: evidence from a spatial Durbin model. Energ Econ 126:106953
Wang CJ, Wang F, Zhang XL et al (2017) Examining the driving factors of energy related carbon emissions using the extended STIRPAT model based on IPAT identity in Xinjiang. Renew Sust Energ Rev 67:51–61
Wang J, Luo X, Zhu J (2022a) Does the digital economy contribute to carbon emissions reduction? A city-level spatial analysis in China. Chin J Popul Resour Environ 20(2):105–114
Wang JD, Wang K, Dong KY et al (2022b) How does the digital economy accelerate global energy justice? Mechanism discussion and empirical test. Energ Econ 114:106315
Wang LP, Long Y, Li C (2022c) Research on the impact mechanism of heterogeneous environmental regulation on enterprise green technology innovation. J Environ Manage 322:116127
Wang LP, Shang YQ, Li C (2023a) How to improve the initiative and effectiveness of enterprises to implement environmental management system certification? J Clean Prod 404:137013
Wang Q, Sun TT, Li RR (2023b) Does artificial intelligence promote green innovation? An assessment based on direct, indirect, spillover, and heterogeneity effects. Energ Environ. https://doi.org/10.1177/0958305X231220520
Wang Y, Zhang YJ, Nie Y et al (2023c) Research on carbon emissions from construction industry based on digital technology: bibliometrics and visual analysis. Industrial Archit 53(S2):32–37
Wang Q, Hu SL, Li RR (2024a) Could information and communication technology(ICT) reduce carbon emissions? The role of trade openness and financial development. Telecommun Policy 48:102699
Wang Q, Sun JY, Pata UK et al (2024b) Digital economy and carbon dioxide emissions: examining the role of threshold variables. Geosci Front 15(3):101644
Wang Q, Zhang FY, Li RR et al (2024c) Does artificial intelligence promote energy transition and curb carbon emissions? The role of trade openness. J Clean Prod 447:141298
Wen ZL, Ye BJ (2014) Analyses of mediating effects: the development of methods and models. Adv Psychol Sci 22(5):731–745
Wu CQ, Deng ML (2023) Impact of digital economy development on industrial carbon productivity in China. China Soft Sci 11:189–200
Wu YN, Al-duais ZAM, Zhu XQ et al (2024) Digital economy's role in shaping carbon emissions in the construction field: Insights from Chinese cities. J Environ Manage 365:121548
Xiang YT, Cui HT, Bi YX (2023) The impact and channel effects of banking competition and government intervention on carbon emissions: evidence from China. Energ Policy 175:113476

Xu WX, Zhou JP, Liu CJ (2022) The impact of digital economy on urban carbon emissions: based on the analysis of spatial effects. Geogr Res-Aust 41(1):111–129
Yang J, Zhong W (2023) Digital empowerment and carbon reduction in the logistics industry: internal mechanisms and empirical evidence. Statistics Decis 39(20):174–178
Yang Z, Gao WJ, Han Q et al (2022) Digitalization and carbon emissions: how does digital city construction affect China's carbon emission reduction? Sustain Cities Soc 87:104201
Yi M, Liu YF, Sheng MS et al (2022) Effects of digital economy on carbon emission reduction: new evidence from China. Energ Policy 171:113271
Yu Z, Liu S, Zhu Z (2022) Has the digital economy reduced carbon emissions? Analysis based on panel data of 278 cities in China. Int J Env Res Pub He 19(18):11814
Zafar MW, Zaidi SAH, Khan NR et al (2019) The impact of natural resources, human capital, and foreign direct investment on the ecological footprint: the case of the united states. Resour Policy 63:101428
Zhang YY, Hu SC (2023) Research on the impact of digital inclusive finance on the coordinated development of economy and environment-mediating effects of innovation-driven. Soft Science 37(09):23–30
Zhang ML, Liu Y (2022) Influence of digital finance and green technology innovation on China's carbon emission efficiency: empirical analysis based on spatial metrology. Sci Total Environ 838:156463
Zhang YH, Wang JT (2020) Can digital economy reduce the factor mismatch of China? Sci Cit Database 35(9):62–71
Zhang LY, Godil DI, Bibi M et al (2021) Caring for the environment: how human capital, natural resources, and economic growth interact with environmental degradation in Pakistan? A dynamic ARDL approach. Sci Total Environ 774:145553
Zhang JN, Lyu YW, Li YT et al (2022a) Digital economy: an innovation driving factor for low-carbon development. Environ Impact Asses 96:106821
Zhang L, Mu RY, Zhan YF et al (2022b) Digital economy, energy efficiency, and carbon emissions: evidence from provincial panel data in China. Sci Total Environ 852:158403
Zhang W, Liu XM, Wang D et al (2022c) Digital economy and carbon emission performance: evidence at China's city level. Energy Policy 165:112927
Zhang PP, Li X, Yu Y (2023a) Relationship between ecosystem services and farmers' well-being in the Yellow River wetland nature reserve of China. Ecol Indic 146:109810
Zhang W, Fan H, Zhao Q (2023b) Seeing green: how does digital infrastructure affect carbon emission intensity? Energ Econ 127:107085
Zhao JX, Mattauch L (2022) When standards have better distributional consequences than carbon taxes. J Environ Econ Manag 116:102747
Zhong ZQ, Chen ZL, He LY (2022) Technological innovation, industrial structural change and carbon emission transferring via trade—An agent-based modeling approach. Technovation 110:102350
Zhou KL, Yang JN, Yang T et al (2023) Spatial and temporal evolution characteristics and spillover effects of China's regional carbon emissions. J Environ Manage 325:116423
Zhu ZC, Liu B, Yu ZX et al (2022) Effects of the digital economy on carbon emissions: evidence from China. Int J Env Res Pub Health 19(15):9450