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Is digital transformation a blessing or a curse for urban low-carbon development efficiency

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The rapid urbanization and industrialization processes have led to changes in land use efficiency, but this has also raised various ecological and environmental issues, especially in the context of highly developed digital economy. How to achieve low-carbon development of urban land has become a global concern. The study investigates how the Internet of Things (IoT) enhances the efficiency of low-carbon cities by examining multiple outcomes, including greenhouse gas emissions, emission intensity, and metropolitan sustainability. Utilizing survey data from 271 Chinese cities from 2010 to 2024, the research employs a comprehensive index of the digital economy to develop a multivariate production index that assesses the success of low-carbon cities. Through fixed-effects modeling and analysis of intermediate impacts, the study explores the influence of the internet-based economy on low-carbon city efficiency. The findings reveal that the digital economy has two primary effects: on a national level, it reduces greenhouse gases and their intensity while simultaneously enhancing the operational efficiency of low-carbon cities. However, the real game-changer is the role of green technology innovations. These innovations, fostered by the digital economy, contribute significantly to a decrease in greenhouse gas emissions and their magnitude, thereby improving the productivity of low-carbon communities. The impact of the internet-based economy on low-carbon city efficiency varies by location, being more pronounced in central and eastern cities. In terms of city size, the digital economy has a more significant effect on smaller and medium-sized towns, reducing their carbon dioxide emissions and enhancing their efficiency as low-carbon cities. However, the efficiency of low-carbon towns is less pronounced in resource-dependent cities, suggesting that resource availability influences the effectiveness of the digital economy in promoting sustainable city development.

KEYWORDS

digital economy, low-carbon city efficiency, green technology innovation, carbon emissions, internet of things (IoT), sustainable development

1 Introduction

Against the backdrop of global efforts to address climate change and promote sustainable development, empowering cities with low-carbon efficiency through the digital economy has become a global issue with distinct characteristics of the times. It transcends the scope of a single country or region and has become a common focus of attention for researchers from various countries. The core lies in how to systematically reshape the energy structure, transportation system, building operation and maintenance, and industrial mode of cities through the deep integration and innovative application of new generation information technologies such as big data, artificial intelligence, and the Internet of Things, achieving accurate monitoring, intelligent decision-making, and dynamic optimization of energy consumption and carbon emissions. This process is not only a technological innovation, but also a key driving force for the profound transformation of urban governance models, production methods, and lifestyles towards greening and intelligence. Therefore, exploring how digital technology can unlock the low-carbon development potential of cities more efficiently and universally, and build smart, livable, and resilient future cities, is a major strategic direction that urgently needs to be deeply researched and practically breakthrough in front of the world.

China has become one of the most vibrant markets globally, exerting significant influence on the global economy as the country with the second-largest Gross Domestic Product (Yusuf and Nasrulddin, 2024). A broad range of human requirements, such as sustenance, energy, transportation, and leisure, propels the ongoing development of the maritime sector. With its geographical expanse of over 3 million square kilometers and a coastline that ranks fourth worldwide, China has an extensive reserve of marine resources. As of 2022, the maritime industry contributed 7.8 percent to China's GDP, totaling 9.4628 trillion Yuan, a 1.9 percent growth compared to the previous year. By mid-2023, the amount has increased by 6 percent to reach 4.7 trillion Yuan. The Bohai Rim, the Yangtze River Delta, and the Pearl River Delta are prominent economic regions known for their thriving maritime sectors, which showcase remarkable resilience and extensive growth (Meng et al., 2024). Notwithstanding the negative impacts of the 2020 COVID-19 epidemic, China's maritime industry has achieved consistent progress since 2009, shifting from a paradigm marked by inefficient operations and growth that generates high pollution levels (Fang et al., 2024). The favorable development can be ascribed to the sector's focus on innovation, collaboration, sustainability, transparency, and cooperation. These values have proven instrumental in driving the industry toward a more sustainable future. Nevertheless, the expansion of China's marine sector is presently limited by ecological and technological obstacles, such as escalating environmental stresses, regional inequalities, and the pressing necessity to establish sustainable and accountable protocols for harnessing marine resources.

Modern technology has emerged as a key driver in the digital transformation of industrial structures, enhancing their capacity to innovate and gain a competitive edge in the digital era (Aldoseri et al., 2024). The maritime sector, in particular, has made significant strides in the development of electronic commerce, boosting economic efficiency and promoting environmental sustainability. Digital technologies have become integral to various subsectors, including marine fisheries, ferry services, renewable marine energy, machinery manufacturing, and marine biotechnology, underscoring the sector's adaptability and resilience (Butt et al., 2024). The integration of networked information systems has empowered the digital economy to revitalize established industries and foster the emergence of new enterprises (Bei et al., 2024). This approach, widely recognized as a viable strategy for achieving a sustainable economy, has facilitated the simultaneous growth of both primary and specialized industries. The increasing convergence of China's technological progress, environmental efforts, and digital economy underscores the need to explore the impact of the digital marketplace on promoting ecological development The digital economy has been pivotal in driving green city development, improving air quality, and advancing sustainable cliticization. Moreover, the correlation between a region's ecological carrying capacity and the stage of its digital transformation further underscores the digital economy's impact on diverse industries such as agriculture and forestry (Ma et al., 2024). The digital economy is progressively replacing traditional economic growth strategies, with the Chinese government actively promoting its advancement as a means to enhance the dynamism and efficiency of the underlying economy. Regional administrations in China are keen on upgrading and transforming historic industries, recognizing the importance of high-emission sectors as gateways for digital expansion. However, shifting traditional industries to peripheral areas to avoid transformation costs presents challenges, including potential environmental degradation and carbon transfer. Therefore, it is crucial to investigate whether relocating industries, driven by the digital economy, leads to the transfer of carbon emissions, underscoring the need for sustainable industrial practices.

In the wake of the recent technological revolution, digital economies have emerged as highly efficient tools for fostering sustainable development. The experience of China, a fast-modernizing country with a growing digital economy, provides essential insights into the simultaneous challenges of environmental management and the necessity for worldwide economic rejuvenation. The primary objective of this study is to investigate the presence of the fossil sanctuary effect in the digital economy, taking into account the consequences of industrial migration. Moreover, the study will enhance the theoretical comprehension of the digital economy and low-carbon development and offer fresh insights into cooperative regional carbon emissions control in China. These results could be standards for other emerging nations that use the digital economy to achieve low-carbon economic expansion and industrial restructuring (Tan et al., 2024). The research explored several critical questions: How did the digital economy influence low-carbon city efficiency and carbon emissions in China's regional economies? What roles did green technology innovations and industrial restructuring play in mediating these effects? Additionally, how did regional disparities and city sizes impact the effectiveness of digital economy initiatives in promoting sustainable development?

The digital marketplace can significantly improve China's industrial sector's green total factor productivity (GTFP). Adopting digitalization in the manufacturing industry is crucial for China to decrease carbon emissions and enhance energy production efficiency. Significantly, geographic areas characterized by sophisticated digital economies typically demonstrate reduced greenhouse gas emissions. Prior research has frequently concentrated on individual variables to evaluate the influence of digital commerce on greenhouse gas emissions, disregarding the complex and diverse dynamics of low-carbon development. An exhaustive evaluation of the impact of the digital marketplace on low-carbon development necessitates the examination of several output indicators, such as overall carbon dioxide emissions, carbon emissions intensity, and efficiency of low-carbon development.

The study aims to examine the many outcomes associated with the digital marketplace to enhance our comprehensive comprehension of its influence on the efficiency of low-carbon growth. The inputs and outcomes of low-carbon practices will be evaluated using the low-carbon development efficiency index, which considers both general and multidimensional objectives. The present study contributes to the existing body of knowledge on the digital marketplace and low-carbon development by investigating the correlation between digital economy activities and the efficiency of low-carbon development from a multimodal perspective. This study will provide significant knowledge for Chinese national and municipal officials, assisting in developing focused approaches to decrease carbon footprints in metropolitan regions. The subsequent sections of this work are organized as follows: Section 2 provides an overview of the pertinent literature. Section 3 presents the theoretical foundation and formulated hypotheses. Section 4 provides a comprehensive account of the research strategy and methodology. Section 5 presents an analysis of a case study. Section 6 analyzes the results, while Section 7 provides policy implications and recommendations.

2 Literature review

The digital economy's role in carbon emissions is a complex and multifaceted topic that has garnered significant attention in recent literature. Studies like those by Wu and Yang (2022) and Tang et al. (2021) highlight the digital economy's dual potential to increase and decrease carbon emissions. On the one hand, digital technologies can optimize energy consumption and improve efficiency, leading to reduced emissions. For instance, integrating Information and Communication Technology (ICT) into various sectors has enhanced energy utilization efficiency and promoted technological advancements that contribute to emission reductions (You et al., 2024). These technologies facilitate better resource management and enable industries to adopt cleaner production processes, ultimately supporting environmental sustainability goals. However, the digital economy's impact on carbon emissions is not uniformly positive. As highlighted by studies such as those by Shahbaz and Sinha (2019) the expansion of digital infrastructure can lead to increased energy consumption, particularly in data centers and communication networks, which may offset the benefits of improved efficiency. This phenomenon is often referred to as the "rebound effect," where the gains in energy efficiency are counteracted by increased demand for digital services. Furthermore, the development of the digital economy can drive economic growth, which may lead to higher overall emissions if not appropriately managed. This underscores the importance of implementing complementary policies and technologies to mitigate these negative effects and ensure that the digital economy contributes to sustainable development. Regional factors also influence the relationship between the digital economy and carbon emissions. Research indicates that the impact of digital economy development varies significantly across different geographic areas, as seen in studies by Zhong et al. (2021). While some regions benefit from reduced emissions due to digital advancements, others may experience increased emissions due to industrial structure and energy consumption patterns. This regional heterogeneity highlights the need for tailored strategies considering local conditions and leveraging the digital economy's potential to drive green growth (Yang et al., 2024). Policymakers must focus on integrating digital technologies with environmental policies to maximize their positive impact and address the specific challenges different regions face. By doing so, the digital economy can play a crucial role in reducing carbon emissions and promoting environmental sustainability on a broader scale.

The relationship between the digital economy and carbon emissions is complex and influenced by several mediating factors. Energy consumption structure is one of the primary mechanisms through which the digital economy impacts carbon emissions. Digital technologies can optimize energy use by improving efficiency in production processes and reducing waste. For instance, Borowski (2021) and Strielkowski et al. (2021) have shown that implementing digital solutions can significantly reduce energy consumption, lowering emissions. These technologies facilitate the transition to more energy-efficient systems, which is crucial for reducing the carbon footprint of industrial activities. By enhancing energy utilization efficiency, digital technologies contribute to a more sustainable economic model. Another critical mechanism is green technology innovation. The digital economy fosters an environment conducive to technological advancements that support sustainability. Innovations in digital technology can lead to cleaner production methods and more efficient resource management practices. Studies by Khuntia et al. (2018) highlight how the digital economy can drive green technology innovations, which in turn help reduce carbon emissions. These innovations often involve integrating advanced technologies like artificial intelligence (AI) and the Internet of Things (IoT), which enable more precise monitoring and control of energy use. Industries adopting these technologies can significantly reduce their environmental impact, contributing to broader efforts to mitigate climate change. Industrial restructuring is another essential factor mediating the relationship between the digital economy and carbon emissions. The digital economy can facilitate the transformation of industrial structures by promoting the shift from high-carbon to low-carbon industries. This transformation is often driven by the need to remain competitive in a rapidly digitizing world. As industries restructure, they can adopt more sustainable practices and technologies, leading to a reduction in carbon emissions. This process is supported by policies that encourage digital innovation and the adoption of green technologies. By understanding these mechanisms, policymakers and industry leaders can better leverage the digital economy to achieve sustainable development goals, ensuring that economic growth is aligned with environmental sustainability.

The concept of regional heterogeneity and spatial effects is crucial in understanding the digital economy's impact on carbon emissions. Several studies, including those by Zhong et al. (2022), have explored how the digital economy can affect carbon emissions across different geographic areas. These variations are often due to differences in regional economic structures, levels of technological adoption, and local government policies. For instance, regions with advanced digital infrastructure and supportive policies may experience significant reductions in carbon emissions as digital technologies optimize energy use and enhance efficiency. In contrast, areas with less developed digital economies may see different benefits.

In some cases, introducing digital technologies could increase emissions due to inefficient implementation or increased energy demand (Ferdaus et al., 2024). This regional heterogeneity underscores the need for tailored approaches to digital economy strategies. Spatial econometric analyses have highlighted that a one-size-fits-all approach is ineffective in maximizing the environmental benefits of the digital economy. Instead, strategies should be customized to leverage specific strengths and address the unique challenges of each region. For example, regions with high industrial activity might focus on integrating digital solutions that enhance energy efficiency and reduce emissions in manufacturing processes. Meanwhile, areas with burgeoning tech sectors might prioritize innovations in green technology and innovative city initiatives. By adopting region-specific strategies, policymakers can better harness the digital economy's potential to drive sustainable development and reduce carbon emissions, ensuring that the benefits are equitably distributed across different geographic areas.

3 Theoretical mechanism and research hypothesis

The philosophy of municipal economic growth is predicated on societal, financial, and environmental sustainability principles (Hutajulu et al., 2024). In the current investigation, three output dimensions utilized to evaluate low carbon efficiency are greenhouse gas emissions, the degree of carbon release, and LCC efficiency (Cui and Cao, 2024). These metrics demonstrate the durability of the attributes above. LCC efficiency signifies harmony in the economy, society, and environment, while carbon emissions indicate a healthy environment. The quantity of carbon emissions indicates sustainability on multiple levels. Therefore, examining how the digital economy affects the efficacy of LCCs in various areas is imperative to contribute to the pursuit of city ecological responsibility. This will expose the relationship between the economy's long-term health, community, ecology, and Internet economics. There are numerous approaches to examining digital commerce's impact on LCC's efficacy.

3.1 Direct impacts of the digital economy on greenhouse gas emissions and low-carbon efficiency

The digital economy, significantly influenced by the rapid advancement of information and communication technologies (ICT), has demonstrated its financial and ecological benefits. This progression, driven by advanced technologies, has reduced greenhouse gas emissions, alleviated carbon burdens, and improved the overall efficacy of life-cycle cost (LCC) management. The power of innovation has established a strong foundation for environmental preservation, optimizing the economic dimensions of green development with tools like cloud computing and machine learning. This technological synergy has seamlessly integrated green technologies with conventional communication infrastructures, enabling continuous government monitoring and evaluation of environmental quality (Shobande et al., 2024). Additionally, the modern digital economy was distinguished by its more effective utilization of resources. Integrating data, knowledge, and other technological components significantly enhanced the efficacy and distribution of traditional resources. The development of the digital economy has provided many benefits, such as the reduction of transactional and informational costs, the promotion of regional industrial advancements, and a substantial decrease in greenhouse gas emissions (Peng et al., 2024). Furthermore, the digital economy's intrinsic benefits and distinctive characteristics, including data sharing and the influence of global exchanges, facilitated the reduction of carbon emissions by reducing the number of redundant processes. Based on these observations, the research hypothesized that the digital economy had the potential to substantially improve the effectiveness of LCC by reducing greenhouse gas emissions and their associated activities.

3.2 Indirect effects of digital innovation on green technology and sustainable city development

This section explores the interconnectedness between digital innovation and sustainable city development, focusing on the role of green technology. Through an analysis of the digital economy's influence, the section highlights how digital platforms and tools contribute to carbon footprint reduction, industrial transformation, regulatory advancements, and the promotion of sustainable living practices. Each subsection delves into specific areas where digital innovation indirectly fosters green technology and supports the transition toward more sustainable cities.

3.2.1 Green technology and the digital economy: catalysts for city carbon footprint reduction

Recent studies have demonstrated that green technology has substantially contributed to reducingcity carbon footprints. The expansion of the Internet economy has further facilitated technological advancements, functioning as a catalyst for innovation in various sectors (Khan and Hassan, 2024). The digital economy has been able to mitigate the disparity in information and the high costs associated with data acquisition, which is one of its primary advantages. The digital economy has facilitated the efficient sharing of creative assets by enabling real-time communication and enhanced transparency through electronic devices. This, in turn, has facilitated the transmission of innovative components across regions while simultaneously enhancing knowledge dissemination and minimizing information leakage (Zhou et al., 2024).

The growing demand for environmentally favorable products and sustainable supply chains, along with the increasing stringency of environmental regulations, has underscored the importance of dual emissions management. In response, businesses have been compelled to implement more sustainable practices, resulting in a decrease in emissions and an increase in energy conservation (Issa, 2024). The pressure to adhere to environmental standards has led to the production of low-emission products and the aggressive development of green technologies. Businesses have been focusing on integrating environmentally favorable solutions into their operations, aligning with global sustainability objectives, and contributing to the broader effort to mitigate climate change.

3.2.2 Revolutionizing industrial structures through digital transformation and environmental sustainability

A profound transformation in how businesses operate and contribute to environmental sustainability has been driven by the digital economy's fundamental reorganization of traditional industries. Initially, modern technologies provided the scientific support and infrastructure required for digital transformation into conventional sectors. A more digital and technology-intensive economy has emerged by seamlessly integrating traditional industries with advanced technologies like the Internet of Things (IoT) and Artificial Intelligence (AI). This integration has transformed the industrial landscape and substantially contributed to reducing greenhouse gas emissions by improving energy efficiency and optimizing production processes.

Moreover, the digital economy has been instrumental in the improvement of secondary market value addition, which in turn has contributed to the reduction of greenhouse gas emissions. The advanced service sector, distinguished by its dependence on digital technologies, has demonstrated its environmental sustainability and economic progressiveness. It has shown that it can outperform traditional manufacturing industries of comparable size in both economic and environmental aspects. The sector's emphasis on sustainability, efficiency, and innovation has facilitated the transition to a low-carbon economy, establishing it as a critical driver of green development. Through these mechanisms, the digital economy has reshaped industrial structures and promoted a more sustainable and environmentally conscious approach to economic growth (Yin et al., 2024).

3.2.3 Enhancing environmental regulation through digital tools in the knowledge economy

Environmental regulation is essential for the reduction of greenhouse gas emissions, the regulation of corporate emissions, and the advancement of sustainable development objectives. Stricter environmental laws have been designated as essential for effectively managing total emission levels across industries, thereby contributing to achieving global sustainability goals. One substantial advantage of technological advancements is their ability to improve regulatory oversight. Continuous surveillance and early warnings of greenhouse gas emissions within specific jurisdictions are facilitated by real-time monitoring and advanced data analytics, enabling more proactive and pinpoint regulatory interventions (Astarita et al., 2024). Additionally, the implementation of a more stringent regulatory framework can serve as a catalyst for technological innovation within companies. Regulations can encourage businesses to develop and implement innovative technologies that reduce environmental impact by enforcing stricter ecological standards. This regulatory pressure has the potential to promote the development of "smart" enterprises, which leverage digital technologies to optimize operations, reduce energy consumption, and reduce carbon emissions. Consequently, stringent environmental regulations not only mitigate the negative environmental impacts of industrial activities but also promote the adoption of more sustainable and technologically advanced business practices, resulting in a decrease in carbon footprints across a variety of sectors (Škare et al., 2024).

3.2.4 Promoting sustainable living in the digital age: the role of digital commerce

In the context of digital commerce, there has been a heightened emphasis on environmental protection and sustainability, which indicates the expanding awareness and responsibility for reducing the ecological impact of consumer activities. Digital platforms have emerged as essential channels for disseminating information on environmental preservation and encouraging behaviors and practices consistent with sustainable, carbon-neutral, and environmentally friendly consumption and travel patterns. The digital realm's extensive availability of information on environmental protection motivates consumers to make well-informed decisions prioritizing ecological integrity. Consumer demands and the economic activities intended to satisfy these requirements are responsible for a substantial portion of energy consumption, exceeding 80% (Gbadeyan et al., 2024). The relationship between consumer behavior and environmental impact underscores the critical role of digital commerce in developing sustainable practices. A study that examined the life-cycle of consumer products in the United States revealed the profound correlation between consumer spending and environmental outcomes. The study underscored the direct and considerable impact of consumers' choices on the nation's energy consumption patterns, encompassing a wide range of factors, including the products they purchase and the modes of transportation they choose. Digital commerce has the potential to considerably reduce the overall environmental footprint by promoting sustainable consumption and travel behaviors, thereby contributing to broader efforts to achieve sustainability goals.

3.2.5 The digital economy's role in transforming energy structures toward sustainability

In particular, the digital marketplace substantially impacts the energy structure by reducing atmospheric carbon dioxide emissions and reliance on coal-based energy. The efficient management of energy is significantly influenced by integrating sophisticated technological tools within the Internet of Things (IoT). These technologies facilitate the proactive surveillance of electricity data, improving energy utilization and gradually transitioning to sustainable energy sources (Hassan et al., 2024). Furthermore, the digital economy facilitates the advancement of green power technologies and the reduction of costs, thereby broadening the scope of sustainable energy applications and expediting the transition from fossil fuel use. This transformation promotes a more resilient and diversified energy landscape and correlates with global initiatives to mitigate climate change and advance environmental sustainability.

3.2.6 Leveraging digital platforms to enhance city carbon sequestration efforts

In addition to reducing carbon production, another critical strategy for reducing carbon emissions is to enhance the capacity of cities to sequester carbon. The quantity of atmospheric carbon dioxide that China's forests physically store is increasing, and the rate at which this occurs is also increasing. Utilizing computerized platforms, carbon storage operations may be dynamically monitored. Furthermore, digital enterprises are actively engaged in establishing forest-based carbon outlets. A joint press release issued by the Institute of Research for the Environmental Environment at the Chinese Academies of the Sciences, in partnership with the World Organization for the Preservation of Nature, conducted an Ants Forest's GEP audit from 2016 to 2020 (Das and Khanikor, 2024). The results indicate that over 3.06 million mu of land were covered by ant woodlands, with over 223 million trees planted during this period. Subsequently, carbon emissions decreased by more than 12 million tons. The LCC technique should be implemented to enhance the carbon sequester function of city green areas, as it fosters low-carbon economic development and enhances the quality of life for individuals. Based on the above arguments, the following hypotheses have been formulated:

> *Hypothesis 1*: The fixed-effect model will effectively capture the impact of direct transfer mechanisms.
>
> *Hypothesis 2*: The internet-based economy can enhance low-carbon city (LCC) effectiveness and reduce greenhouse gas emissions by promoting innovations in green technologies.

Figure 1 depicts the influence of the digital economy on Low-Carbon City (LCC) efficiency in city areas, where LCC efficiency represents a balance between economic, social, and environmental wellbeing. This concept considered vital factors such as greenhouse gas emissions, carbon intensity—the amount of carbon released per unit of economic output—and overall LCC efficiency. The digital economy directly impacted LCC efficiency by reducing greenhouse gas emissions. This reduction was achieved through advancements in information and communication technologies (ICT), which facilitated lower emissions through various innovative approaches. Additionally, the digital economy indirectly influenced LCC efficiency through multiple mechanisms. It promoted green technology innovation, fostering, developing, and disseminating technologies designed to minimize carbon footprints. Furthermore, it contributed to improved industrial structures by integrating digital technologies like Artificial Intelligence (AI) and the Internet of Things (IoT), which transformed industries, enhanced efficiency, and reduced emissions. The digital economy also supported stricter environmental regulations, enabling better monitoring and enforcement and lowering emissions. Moreover, digital platforms played a role in raising awareness about environmental issues, promoting sustainable consumption patterns, and supporting the transformation of energy structures. This transformation included the increased use of renewable energy sources and reduced reliance on fossil fuels. Finally, the digital economy enhanced carbon sink capacity by improving the monitoring and management of carbon sequestration efforts, such as tree planting initiatives.

4 Methodological framework: analyzing digital economy's impact on low-carbon city efficiency

This section outlines the methodological framework employed to assess the digital economy's influence on the efficiency of low-carbon cities (LCCs). It integrates fixed-effect models and mediation analysis to understand direct and indirect effects, providing a comprehensive view of how digital advancements contribute to sustainable city development.

4.1 Fixed-effect and mediation analysis

The fixed-impact approach works well for internal problems caused by missing factors. A subsequent fixed-effect foundation regression equation is built to confirm hypothesis 1 in the direct transfer scenario.

$$Y_{it} = \alpha_0 + \alpha_1 Dig_{it} + \beta X_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

In this case, "i" denotes the city, and "t" denotes the year. Y stands for the parameter that is reliant on others α_0 signifies a fixed phrase, α_1 is the approximated variable of the electronic economy.

Dig_{it} Shows a measure of the rise of the digital finance of city i duration of time t, and is the major contributing factor.X_{it}Are the factors that influence the efficiency of environmentally friendlycity areas μ_i stands for the town's permanent impact δ_t stands for the constant impact of a period of time, ε_{it} stands for the phrase that denotes noise.

For the second study hypothesis, a mediation impact framework was built to talk about the potential indirect effects of the digital economy on LCC achievement, as well as the immediate implications. The following are the exact procedures: Assuming $\alpha 1$ is significantly different, we can build the electronic economy regression (Equation 2) for intermediate variables in combination and the LCC effectiveness predictor (Equation 3) for digital economic and intermediate variables separately. Here are the specifics, using the example.

$$M_{it} = b_0 + b_1 Dig_{it} + bX_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

$$Y_{it} = c_0 + c_1 Dig_{it} + c_2 M_{it} + cX_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

Where M_{it} stands as the moderating variable encompassing carbon sinks, low-carbon lifestyles, technological advances, manufacturing systems, environmental laws and regulations, and power structures. Assuming the importance of the factor b_1 in Equation 2 and c_2 is unaltered in Equation 3, yet the significance and ultimate worth of c_1 n Equation 3 drops dramatically compared to α_1

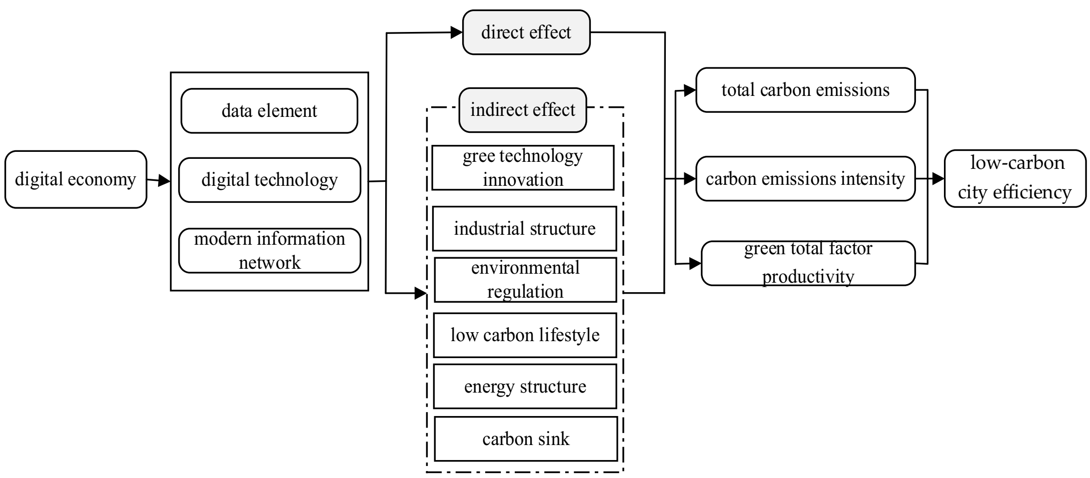

FIGURE 1
The impact of the digital economy on LCC efficiency, both directly and indirectly.

determined by the parameter in Equation 1 M_{it} acts as a go-between for the digital economy and the efficiency of LCCs.

4.2 Evaluating low-carbon city efficiency

The present investigation utilizes multivariate outcome indices of LCC efficiency, which include total emissions of carbon (CE), carbon emissions intensity (CI), as well as low climate city efficiency (LCCE). Some research are among the prior investigations that have used carbon footprints, per capita carbon dioxide emission levels, greenhouse gas magnitude, and LCC productivity as signs to evaluate LCC efficiency. The effect of the Internet economy index on each of these metrics was computed in this research. It was noted, however, that greenhouse gas emissions and individual carbon emissions produce comparable outcomes. The three indices described earlier were thus chosen as the final metrics for evaluating LCC efficiency.

1 Carbon dioxide emissions as a whole (CE)

By taking the town's carbon releases and multiplying them by a logarithm operation, the total carbon emissions can be determined using the approach put forward by particular, the methane emission caused by using natural gasNGas. Natural gas in a liquid state LPG and electricity Elec for use as energy sources. Building the Equation 4 in the following way:

$$CO_2 = \sigma_1 \mathrm{NGas} + \sigma_2 \mathrm{LPG} + \sigma_3 \left(\mathrm{k} \times \mathrm{Elec}\right) \tag{4}$$

Where σ_1 shows NGas the value of the carbon footprint coefficient is 2.1622 kg/m3. σ_2 ShowsLPG A coefficient for carbon emissions, with an estimate of 3.1013 kg/kg. ó$_3$ means the coal-fired fuel's greenhouse gas emissions factor, measured in 1.3023 kg/kWh; k provides a numerical representation of the percentage of the total output of electricity that comes from coal-fired generators.

2 The intensity of carbon emissions (CI)

Finding the proportion of greenhouse gas emissions to GDP is the first step in calculating the degree of carbon dioxide emissions.

3 Efficient environmentally friendly city planning

The super-SBM approach, grounded in Xue et al.'s (2024) research, was used to determine the effectiveness of environmentally friendly cities.

The specific model expression is shown in Equation 5:

$$\min GTFP = \frac{1 + \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{ik}}}{1 - \frac{1}{q_1 + q_2}\left(\sum_{r=1}^{q_1} \frac{s_i^+}{y_{rk}} + \sum_{t=1}^{q_2} \frac{s_t^{b^-}}{b_{tk}}\right)}$$
$$s.t. \begin{cases} \sum_{j=1, j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik} \\ \sum_{j=1, j\neq k}^{n} y_{rj}\lambda_j + s_r^+ \geq y_{rk} \\ \sum_{j=1, j\neq k}^{n} b_{tj}\lambda_j - s_t^b \leq b_{tk} \\ 1 - \frac{1}{q_1 + q_2}\left(\sum_{r=1}^{q_1} \frac{s_i^+}{y_{rk}} + \sum_{t=1}^{q_2} \frac{s_t^{b^-}}{b_{tk}}\right) > 0 \end{cases} \tag{5}$$

In Equation 5, the decision-making unit DMU for total factor carbon productivity is n, The input variable is x_i, the expected output is y_r, and the unexpected output is b_t; s_i^-, s_r^+, s_t^b are the slack variables of input, expected output, and unexpected output, respectively; *TFCP* represents the green total factor productivity.

Figure 2 illustrates the conceptual framework used to analyze the impact of the digital economy on Low-Carbon City (LCC) efficiency. This framework outlines the critical input and output variables considered in the study.

The input variables included the labor force, encompassing both the size and quality of labor crucial for economic growth and development.

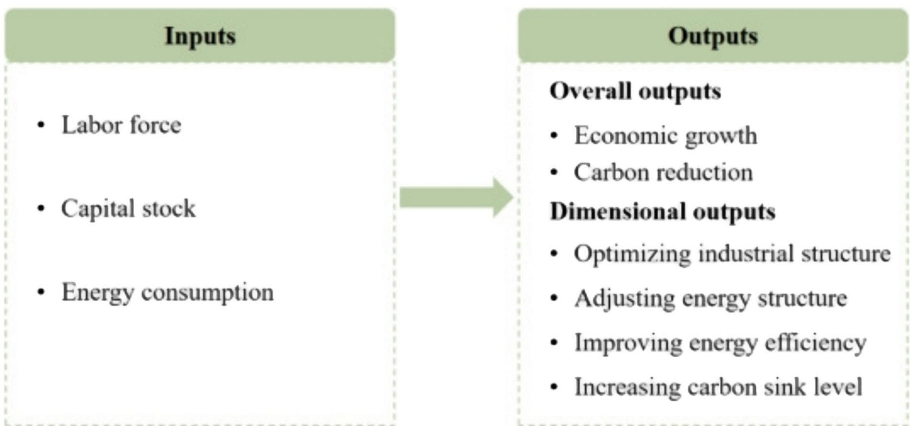

FIGURE 2
The parameters used in LCCE for input and outcome.

Capital stock, comprising physical and human capital such as infrastructure, machinery, and technology, was also an essential input, facilitating production and innovation. Energy consumption, another critical input, represents energy resources necessary for economic activities, which could have significant environmental implications. The output variables were categorized into overall outputs and dimensional outputs. Overall outputs measured economic growth, indicated by the increase in GDP over time, reflecting the broader economic efficiency. Carbon reduction, signifying the decrease in greenhouse gas emissions, was another overall output, highlighting the environmental impact of financial activities. Dimensional output focused on specific areas, such as optimizing the industrial structure, which involved shifting toward more sustainable and efficient industrial sectors. Adjusting the energy structure referred to the transition from fossil fuels to renewable energy sources, while improving energy efficiency measured the reduction in energy consumption per unit of economic output. Additionally, increasing the carbon sink level indicated the enhancement of natural carbon sinks, such as forests, to absorb carbon dioxide. The research methodology employed a fixed-effect model to control unobserved heterogeneity across cities and periods, ensuring a more accurate estimation of the relationship between the digital economy and LCC efficiency. Mediation analysis was also utilized to examine the indirect effects of the digital economy on LCC efficiency through intermediate variables, including green technology innovation, industrial structure, environmental regulation, sustainable living, energy structure, and carbon sink capacity. The dependent variable, LCC efficiency, was measured using three indicators. Total carbon emissions (CE) represent a city's overall amount of carbon dioxide. Carbon emissions intensity (CI) measures the amount of carbon emissions per unit of GDP. Low-Carbon City Efficiency (LCCE) assesses a city's efficiency in reducing carbon emissions and promoting sustainable development.

4.3 Control variable: contextual factors influencing carbon emissions: a multidimensional approach to control variables

The efficiency of low carbon consumption (LCC) efficiency can be substantially influenced by various control factors, as well as the digital economy. Incorporating these control factors into static models reduces estimation bias and ensures a precise evaluation. Parameters that frequently and significantly influence carbon dioxide emissions are identified in Table A1 of the accompanying document. Six critical criteria have been selected—Economic Development (ED), Population Size (PS), Science and Technology (ST), Financial Development (FD), Human Capital (HC), and Foreign Direct Investment (FDI)—in addition to economic growth, human resources, and foreign direct investment—because numerous studies have implemented a variety of metrics as control variables. Enhanced environmental awareness and an improved quality of life are frequently linked to economic development (ED), which is associated with economic growth. This study quantifies economic progress by calculating per capita income, which is derived from the logarithm of GDP per person. This methodology provides insight into the correlation between environmental practices and economic development. City areas' population size (PS) can have a dual impact. On the one hand, increasing population may result in higher energy consumption and carbon emissions. Conversely, the aggregation effect of a larger population can enhance the efficacy of carbon dioxide emissions management. Population density, calculated as the logarithm of the total number of city residents divided by the total surface area of the city's administrative zone, is used in this study to evaluate this aspect.

Science and technology (ST) are essential for improving city energy efficiency. Scientific and technological research can foster innovation and enhance energy management practices. Technological advancements are evaluated by comparing the proportion of GDP allocated to scientific and technological activities. Financial development (FD) can influence carbon emissions in both positive and negative ways. On the positive side, economic growth can promote environmentally friendly methods and improve manufacturing processes, thus reducing costs. However, it may also increase greenhouse gas emissions by boosting GDP growth and energy consumption, particularly of fossil fuels. In this investigation, the ratio of GDP allocated to financial institutions is used to assess economic development. Human Capital (HC) reflects a city's capacity to cultivate talent and promote societal advancement. Increased educational attainment and awareness of environmental issues associated with human capital can stimulate innovation and reduce emissions. In this study, the proportion of students enrolled in postsecondary education relative to the total student population serves as a metric for human capital. Foreign Direct Investment (FDI) has a dual effect on environmental sustainability. While FDI can encourage the adoption of environmentally favorable technologies and reduce pollution, it may also exacerbate environmental issues by facilitating the relocation of polluting industries. The impact of foreign direct investment (FDI) on environmental stewardship and sustainability is evaluated by calculating the ratio of FDI to GDP.

4.4 Mediating factor: unpacking the mediating mechanisms: how green innovation and infrastructure shape city carbon efficiency

The mediating factors employed in the preceding research are elaborated upon in Table A2 of the appendix. The data presented has identified five critical parameters as mediating variables: ecological regulations, economic infrastructure, environmentally friendly lifestyle, technological advancement, and electricity structure. Carbon Sink is a critical factor in implementing low-carbon consumption (LCC). Green technological innovations (GTI) significantly influence city economic growth. GTI has an immediate impact on the standard of city financial development, while creativity promotes high-quality growth. This study employs the number of green patent applications per capita (M1), as determined by the State-run Public Properties Administration of China, to represent GTI. M1 is calculated by dividing the total number of regional environmental patent applications by population derived from the World Intellectual Property Organization's (WIPO) environmental technology list.

$$M2 = S1 \times 1 + S2 \times 2 + S3 \times 3 \quad (6)$$

Another critical mediating factor is the infrastructure for industry (IS). A more optimized manufacturing system can facilitate the reduction of greenhouse gas emissions. The manufacturing structure parameter (M2) is determined by the percentage of local GDP produced by the S1, S2, and S3 sectors. Economic infrastructure's efficacy is contingent upon this parameter. Ecological regulations (ER) substantially affect carbon emissions. Environmentally favorable legislation has the potential to reduce pollution and financial output, thereby reducing carbon emissions over time. This investigation evaluates environmental management by analyzing the abundance of ecological terminology in municipal government reports at the prefecture level (M3).

The Low-Carbon Lifestyle (LCL) reflects the growing public concern regarding carbon emissions, which is a result of the increasing rate of social and economic mobility. The proportion of electric vehicles per 10,000 people (M4) measures the environmental friendliness of city lifestyles. Carbon emissions are also influenced by energy structure (ES). The energy use pattern is critical because different energy sources have varying carbon contents. This facet is assessed by comparing the proportion of coal consumption to total energy consumption (M5). A carbon sink (CS) is indispensable for reducing carbon emissions and improving cities' carbon storage capacity. Forests, vegetation, and pastures are examples of city green spaces contributing to carbon sequestration. The efficacy of a carbon sink is determined by the rate of vegetative cover in a specific area (M6). The coverage rate of a carbon sink is directly proportional to its effectiveness.

4.5 Independent variable: the digital economy as a catalyst for sustainable city development: measuring digital economic impact

The autonomous factor is the Digital Economy Development (DED) extensive score. Ma et al. (2024) published a groundbreaking research paper on the digital economy in the esteemed magazine "The Field of Technology in Society" in 2022. This paper is cited in the DED comprehensive index and rating system. Other researchers have cited these findings, which serve as additional evidence of their significance. This research is consistent with a substantial corpus of prior research on the effectiveness of DEDs. For example, Zhang and Li (2024) employed the same set of metrics to assess the efficiency of DEDs. Consequently, Table 1 displays the selected indices to evaluate the efficacy of DED.

The measures of the digital economy developed for this research are captured through four key dimensions, each with a positive attribute indicating their beneficial impact on the digital economy. The first dimension, Internet-Related Employees, is measured by the rate of computer services and software workers as a percentage of the total workforce. A higher percentage suggests a robust digital economy, reflecting a significant portion of the workforce engaged in internet-related activities. The second dimension, Internet-Related Output, is assessed by the total number of telecom services per capita, measured in Yuan. This indicator signifies the economic contribution of internet-related services, with higher values indicating a well-developed digital infrastructure. The third dimension, Mobile Internet Users, is gauged by the density of mobile phone consumers relative to the total population. This measure reflects the penetration of mobile internet usage, where a higher density indicates widespread access and integration of mobile internet services. Lastly, Internet Penetration is measured by the number of internet users per one hundred people, highlighting the extent of internet usage within the population. A higher number signifies greater internet penetration, indicating the accessibility and integration of digital technology in everyday life. Collectively, these dimensions provide a comprehensive understanding of the digital economy's development, emphasizing the importance of workforce engagement, economic Output, and user penetration in fostering digital economic growth.

TABLE 1 Measures of the digital economy were developed for this research.

Dimensions	Indicators (Unit)	Attribute
Internet-related employees	Rate of computer services and software workers (%)	Positive
Internet-related output	Total number of telecom services per capita (Yuan)	Positive
Mobile Internet users	The density of consumers of mobile phones relative to the total population	Positive
Internet penetration	Number of people using internet access per one hundred (Users with 100 people)	Positive

The methods for data collection and the sources of the numerous indicators utilized in the research are delineated in Table 2. The indicators and their respective measuring methodologies are intended to capture various environmental and economic metrics aspects. The logarithm of carbon emissions is employed to quantify carbon emissions (CE) with data from the Statistics Yearbook of China Power Metropolis. The China city Statistical Yearbook calculates Carbon Intensity (CI) as carbon emissions per GDP. A super-SBM model is employed to determine Low-Carbon City Efficiency (LCCE) by analyzing primary data from various sources, such as the China Energy City Statistical Yearbook, China Statistical Yearbook, and China city Statistical Yearbook. The logarithm of per capita GDP is measured by the indicator C1, while C2 assesses the logarithm of the population relative to the city administrative district area. Both indicators are derived from the China city Statistical Yearbook. C3 assesses expenditures on science and technology as a percentage of GDP, C4 measures loans made to financial institutions relative to GDP, C5 calculates the ratio of college and university students to the total population, and C6 evaluates actual Foreign Direct Investment (FDI) as a percentage of GDP, all using data from the same yearbook. The State Intellectual Property Office of China and the China city Statistical Yearbook are the sources of M1, a metric that quantifies the number of green patent applications per capita. The three industrial structures determine M2, the PKULAW database determines M3, M4 is a percentage of the population that measures the density of electric cars, M5 is a calculation of coal consumption about overall energy consumption, and M6 is a measurement of the rate of green vegetation in finished areas, with data sourced from a variety of statistical yearbooks. Finally, the China city Statistical Yearbook and the China Energy City Statistical Yearbook are used to calculate Digital Economy Development (DED) using a PCA model. Collectively, these indicators establish a comprehensive framework for examining the relationship between economic activities and environmental impacts in city areas of China.

5 Case study

5.1 Leveraging big data for sustainable development: a comprehensive analysis of 271 Chinese cities

The sample size is a critical factor in applying these models, as small numbers may result in unpredictability. It is imperative to select

TABLE 2 Methods for collecting data and where to find indicators.

Indicators	Measuring method	Data source
CE	Logarithm of carbon emissions	The Statistics Yearbook of China Power Metropolis
CI	Carbon emissions/GDP	China city Statistical Yearbook
LCCE	Calculated based on super-SBM model using raw data	China Energy City Statistical Yearbook, China Statistical Yearbook, China city Statistical Yearbook
C1	Logarithm of per capita GDP	China city Statistical Yearbook
C2	Logarithm of the population/ urban administrative district area	China city Statistical Yearbook
C3	Expenditure on science and technology/GDP	China city Statistical Yearbook
C4	Loans made to financial institutions/GDP	China city Statistical Yearbook
C5	College and university students/the total population	China city Statistical Yearbook
C6	Actual FDI/GDP	China city Statistical Yearbook
M1	Per capita green patent applications	The State Intellectual Property Office of China, China city Statistical Yearbook
M2	Calculated based on the three industrial structure	China city Statistical Yearbook
M3	Word frequency in ecological vocab and work reports from prefectural-level cities	PKULAW database
M4	Electric car density as a percentage of the population	China city Statistical Yearbook
M5	Coal consumption/overall energy consumption	China city Statistical Yearbook
M6	The rate with green vegetation for the finished area	Statistics Yearbook of China's Cities
DED	Calculated based on the PCA model using raw data	China city Statistical Yearbook, China Energy City Statistical Yearbook

an appropriate sample size to ensure the precision and dependability of the investigation. Research has demonstrated that the Internet of Things impacts carbon intensities. The specific result analysis of the data presentation is as follows:

Firstly, the development process and mode transformation. In the past 15 years, 271 cities in China have undergone significant evolution from initial exploration to systematic deepening in using big data to promote low-carbon development. In the early stages, big data applications were mainly focused on policy pilots and infrastructure construction in individual fields, such as industrial energy consumption monitoring. With the passage of time, its application scope has rapidly expanded and its depth has continuously increased, gradually evolving into a core force driving the overall carbon reduction of cities. This process has achieved a systematic transformation from decentralized and single point technological attempts to comprehensive and deep integration with urban energy structure, industrial structure, transportation system, and governance mode, marking a fundamental shift from experience driven to data-driven and intelligent low-carbon governance mode.

Secondly, the key driving forces and urban differences. The key driving force behind this transformation process lies in the synergy between national top-level design and local pilot innovation. The combined effect of policies such as "smart cities," "national big data comprehensive pilot zones," and "low-carbon pilot cities" provides a clear policy framework and practical field for big data to empower low-carbon development. However, the effectiveness of big data emission reduction shows significant differences among 271 cities. Usually, developed eastern regions and mega cities, with their superior economic foundation, technological talents, and infrastructure, can more efficiently utilize big data, forming a pattern of "high in the east and low in the west" and "big cities leading." The technological paths of resource-based cities and tertiary industry dominated cities also vary depending on their endowments.

Thirdly, future trends and prospects. Looking toward the future, the path of "digital low-carbon" in Chinese cities will present a trend of deep integration and refined management. Technologically, artificial intelligence and fifth generation mobile communication will be more closely integrated with carbon management to enhance the accuracy of prediction and optimization. In terms of management, the granularity of carbon emission control will continue to be refined, from city level platforms to park, community, and even building levels, achieving more extreme energy conservation and emission reduction. At the same time, market-oriented mechanisms such as green finance and carbon trading markets will be deeply linked with big data platforms to inject sustained economic momentum into the low-carbon transformation of cities, ultimately promoting the construction of smart, green, and resilient future cities.

5.2 Assessing the impact of the digital economy on carbon emissions: a City-level investigation

Spatial geographical analysis of narrow with results of the fundamental analysis, which addresses endogenous variables issues, are presented in Table 3. The table illustrates the impact of the digital market on the efficacy of LCCs after accounting for characteristics such as management, city-fixed consequences, and year-fixed consequences. Thus, the data presented in columns (1) and (2) of Table 3 indicate that the anticipated impacts on total and city carbon dioxide emissions from the digital economy are statistically significant and negative at the 1 and 5% levels. The utilization of technology substantially reduces greenhouse gases at the city level, both in magnitude and in totality, on a national scale. At the 5% significance level, the computed coefficients in columns (3) of 0.030 suggest a beneficial correlation between the efficacy of LCCs and the digital sector. To be more precise, the efficacy of a town's LCC increases by 0.030 units for every 5% increase in the Internet economy index. The findings further support the initial hypothesis. Financial growth and the density of populations, which are considered controllable factors, have a substantial impact on the release of carbon and concentration. As economic and demographic factors increase, certain regions experience a decrease in emission intensity and an increase in greenhouse gas emissions. The efficiency of LCCs is influenced by the amount of money spent on research and development—precisely, a higher level of R&D expenditure results in higher LCC efficiency.

5.3 Validating the digital economy's role in carbon reduction: a robustness analysis across Chinese cities

The study employs a series of robustness tests to further validate the accuracy of the empirical evidence. The analysis begins with a reduction strategy, where a new estimation experiment was conducted, omitting measurements related to carbon emission effectiveness at the extreme 1% level due to the impact of the highest values on the overall sample. The results in columns (1)–(3) of Table 4 indicate that LCC effectiveness is enhanced, and the digital marketplace contributes to reducing the total amount and degree of greenhouse gas emissions in metropolitan areas. These outcomes are consistent with the findings of the initial regression analysis.

Table 4 illustrates the results of the resilience analysis, emphasizing the correlation between the development of the digital economy (DED) and various economic and environmental indicators. The study employs six models, each of which analyzes distinct combinations of dependent variables: carbon intensity (CI), low-carbon city efficiency (LCCE), and the logarithm of carbon emissions (lnCE). The results suggest that DED has a substantial negative impact on carbon intensity (CI) and carbon emissions (lnCE), with coefficients of −0.081 and −0.038 in models (1) and (2), respectively, and −0.068 and −0.042 in models (4) and (5). This implies that the digital economy's advancements contribute to reducing carbon emissions and intensity. In contrast, the coefficients of 0.031 and 0.033 in models (3) and (6) suggest that digital economy initiatives improve low-carbon efficiency in cities, indicating that DED positively impacts LCCE. Mixed effects are observed for other variables, including the logarithm of economic development (lnED) and population size (lnPS). lnED has a positive and substantial influence on carbon emissions but a negative effect on carbon intensity. This implies that economic growth increases emissions but reduces emissions per unit of GDP. DPS also has a similar effect, increasing emissions while decreasing carbon intensity, underscoring the intricate relationship between population growth and environmental impact. The current investments may need to be more effectively translated into low-carbon efficiencies, as science and technology expenditures (ST) negatively influence LCCE. Foreign direct investment (FDI), human capital (HC), and financial development (FD) exhibit largely insignificant effects in all models.

The analysis incorporates fixed effects for city and year to ensure that the results represent unobserved heterogeneity across cities and over time. The adjusted R-squared values suggest that the included variables effectively reflect the variations in these outcomes, particularly for lnCE and CI, indicating a high level of explanatory power for the models. In general, the results emphasize the digital economy's positive impact on environmental sustainability and the necessity of additional enhancements to improve the efficacy of low-carbon cities.

TABLE 3 Findings from studying how the rise of the digital economy has affected emission reductions.

Variables	(1)	(2)	(3)
	Ln CE	CI	LCCE
DED	−0.076***	−0.046**	0.030**
	(−2.794)	(−2.055)	(2.067)
lnED	0.641***	−0.381***	0.041
	(5.916)	(−3.005)	(0.763)
lnPS	0.421***	−0.455***	0.045
	(3.295)	(−3.107)	(0.769)
ST	−0.071	−0.088	−0.178***
	(−0.811)	(−1.114)	(−2.947)
FD	0.045	0.179	0.002
	(0.509)	(1.069)	(0.057)
HC	−0.033	−0.049	−0.005
	(−0.826)	(−1.302)	(−0.243)
FDI	0.008	0.008	−0.005
	(0.997)	(0.823)	(−1.103)
_cons	−0.802	8.058***	0.387
	(−0.405)	(3.354)	(0.397)
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
N	3,978	3,978	3,978
adj. R^2	0.907	0.662	0.539

***, **indicates significance at the 1%, 5% level.

5.4 Unpacking the digital economy's influence: mechanisms for enhancing low-carbon efficiency and reducing emissions

The regression analysis from the benchmarking research reveals that the digital economy has the potential to enhance low carbon consumption (LCC) efficiency while concurrently diminishing both the total amount and the severity of carbon emissions. This dual benefit raises the question of how such improvements are achieved. To address this, Models (2) and (3) were employed to assess the underlying processes and mechanisms through which the digital economy exerts its influence. The detailed findings of these evaluations are presented in Table 5, which elucidates how integrating digital technologies and platforms facilitates more efficient carbon management and promotes environmental sustainability. At the 5 % barrier, the estimated coefficient for the digital economy in column (1) of Table 5 is 0.484, indicating a significant favorable influence. This demonstrates that the internet marketplace has the potential to foster ecologically sustainable technological advancements. They are adding innovation in green technology to the data in column (2), which results in an unfavorable core explaining the coefficients of the variable, which subsequently decreases. These findings indicate that implementing more environmentally friendly technology and innovative thinking in the digital industry could mitigate the emission of carbon dioxide. Furthermore, the quantity of the significant descriptive variable decreases dramatically while maintaining a high coefficient when green progress in technology is represented in

TABLE 4 The outcomes of the resilience analysis.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	lnCE	CI	LCCE	lnCE	CI	LCCE
DED	−0.081***	−0.038***	0.031***	−0.068**	−0.042***	0.033**
	(−2.720)	(−1.693)	(1.916)	(−2.367)	(−1.749)	(2.157)
lnED	0.618***	−0.250***	0.055	0.647***	−0.380***	0.038**
	(5.966)	(−2.690)	(1.076)	(5.959)	(−2.972)	(0.707)
lnPS	0.247**	−0.306**	0.051	0.440***	−0.446***	0.039
	(2.029)	(−2.541)	(1.015)	(3.475)	(−3.033)	(0.659)
ST	−0.022	−0.106	−0.283***	−0.073	−0.086	−0.184***
	(−0.176)	(−1.172)	(−3.973)	(−0.822)	(−1.073)	(−2.929)
FD	0.082	0.064	0.006	0.033	0.174	−0.000
	(0.946)	(0.790)	(0.142)	(0.376)	(1.033)	(−0.013)
HC	−0.026	−0.023	−0.011	−0.037	−0.051	−0.005
	(−0.608)	(−0.679)	(−0.586)	(−0.920)	(−1.355)	(−0.256)
FDI	0.006	0.000	−0.007	0.004	0.006	−0.005
	(0.711)	(0.013)	(−1.207)	(0.564)	(0.604)	(−1.051)
_cons	0.253	5.692***	0.336	−2.137	7.288***	−0.021
	(0.146)	(3.172)	(0.394)	(−1.200)	(3.322)	(−0.023)
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
N	3,978	3,978	3,978	3,918	3,918	3,918
adj. R^2	0.907	0.736	0.543	0.900	0.663	0.531

***, **indicates significance at the 1%, 5% level.

column (4). This illustrates how environmentally aware technical advancements might help the digital economy become more efficient regarding life cycle cost. Analysis of column (1) reveals an unforeseen absence of a statistically significant correlation between the Internet economy and the industrial system, notwithstanding the positive impact. The strategies used by the federal government to promote the growing digital economy have stimulated increased expenditure in several industries, promoting transformations in the manufacturing system and decreasing greenhouse gas emissions. Another plausible rationale is the rapid advancement of digital technologies such as cloud storage and artificial intelligence (AI).

Nevertheless, they represent the optimal result. The conclusions of this study indicate that the electronic economy has a modest yet beneficial impact on the economic structure. Geng et al. (2024) present pertinent statistical evidence suggesting that altering the composition of the manufacturing industry will not lead to a total mitigation of carbon dioxide emissions. Yin et al. (2024) argue that significant changes can influence the effectiveness of carbon emission reduction efforts resulting from industry restructuring in primary and tertiary sectors and local economic and corporate structures. The findings in Table 5 support the claim that carbon-free travel and more stringent environmental regulations are outcomes of the digital marketplace. However, these factors alone have not achieved the desired level of carbon reduction. Energy consumption also exerts a mediating effect. Modifying the fundamental principles of energy consumption demonstrates that digital commerce does not substantially reduce greenhouse gas emissions. Firstly, the country's energy consumption system depends significantly on high-carbon energy sources due to limitations imposed by natural resources. This poses challenges in promptly implementing changes and results in little immediate visibility of the benefits of reducing greenhouse gas emissions. Furthermore, attempting to improve the electrical power system by increasing renewable energy is expensive and imposes additional economic strain, complicating efforts to mitigate climate change. Lastly, the function of carbon sinks as intermediates is studied. While the emergence of the internet promotes carbon sinks, the consequences of this phenomenon may require a considerable amount of time to become evident. The process's study suggests that advancements in green technology within the digital sector have the potential to reduce greenhouse gas emissions and enhance LCC production effectively. Some body of evidence exists that substantiates hypothesis 2.

5.5 Regional and city disparities in low-carbon efficiency: analyzing the heterogeneous impacts of the digital economy

The relationship between these factors is expected to vary due to the significant regional variation in carbon emissions and technological innovation levels. By employing a variance analysis that takes into account three dimensions: local geographic region, municipal size, and resource type, this study improves comprehension of how the digital market affects the effectiveness of LCCs. Table 6 examines the heterogeneous impacts of the digital economy on low-carbon city efficiency (LCCE) across different regions in China, categorized by the National Bureau of Information into eastern, central, western, and

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TABLE 5 Mechanism evaluation.

Variables	(1)	(2)	(3)	(4)
	GTI	lnCE	CI	LCCE
DED	0.484**	−0.055**	−0.033	0.024*
	(2.146)	(−2.241)	(−1.507)	(1.666)
GTI		−0.044***	−0.027***	0.012***
		(−5.556)	(−4.342)	(2.991)
adj. R^2	0.727	0.909	0.664	0.541
Variables	IS	lnCE	CI	LCCE
DED	0.003	−0.077***	−0.049**	0.028*
	(1.229)	(−2.946)	(−2.224)	(1.934)
IS		0.765**	0.812**	0.593***
		(2.560)	(2.055)	(3.296)
adj. R^2	0.910	0.907	0.664	0.545
Variables	ER	lnCE	CI	LCCE
DED	0.004	−0.077***	−0.047**	0.030**
	(0.572)	(−2.828)	(−2.098)	(2.057)
ER		0.085	0.121*	0.024
		(1.208)	(1.690)	(0.702)
adj. R^2	0.910	0.906	0.664	0.545
Variables	LCL	lnCE	CI	LCCE
DED	0.028	−0.076***	−0.046**	0.030**
	(0.418)	(−2.785)	(−2.052)	(2.052)
LCL		−0.010*	0.003	0.005*
		(−1.726)	(0.274)	(1.929)
adj. R^2	0.771	0.907	0.662	0.539
Variables	ES	lnCE	CI	LCCE
DED	−0.142	−0.073***	−0.045**	0.029**
	(−0.225)	(−3.127)	(−2.114)	(2.221)
ES		0.018***	0.008*	−0.009***
		(5.381)	(1.854)	(−10.483)
adj. R^2	0.735	0.919	0.669	0.577
Variables	CS	lnCE	CI	LCCE
DED	1.788	−0.080***	−0.048**	0.030**
	(1.165)	(−2.960)	(−2.166)	(2.075)
CS		0.002**	0.001**	−0.000
	(−0.488)	(−0.392)	(3.363)	(0.396)
adj. R^2	0.378	0.907	0.662	0.539
N	3,978	3,978	3,978	3,978
Controls	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

***, **indicates significance at the 1%, 5% level.

northeastern areas. The table reveals that the effects of the digital economy on carbon emissions and LCCE vary significantly by region. In the Eastern Region, digital economy development (DED) has a modest negative impact on the logarithm of carbon emissions (lnCE) with a coefficient of −0.076, significant at the 10% level, indicating a slight reduction in emissions. However, its effects on carbon intensity (CI) and LCCE are not statistically significant, suggesting limited influence on these aspects in this region. The adjusted R-squared values indicate a robust model fit for lnCE (0.929) but moderate for CI (0.546) and LCCE (0.579). In the Central Region, DED shows a more pronounced negative impact on both lnCE (−0.152) and CI (−0.085), both significant at the 5% level, demonstrating a substantial reduction in emissions and intensity. Additionally, DED positively influences LCCE (0.062), which is also significant at the 5% level, indicating improved low-carbon efficiency. The adjusted R-squared values are high for lnCE (0.893) and moderate for CI (0.632) and LCCE (0.555), suggesting an excellent explanatory power of the models. The Western Region shows no significant effects of DED on lnCE, CI, or LCCE, with coefficients of −0.024, −0.075, and −0.002, respectively, indicating that the digital economy's influence is minimal in this area. The adjusted R-squared values are high for CI (0.695) but lower for lnCE (0.878) and LCCE (0.455), reflecting varying model fits. In the Northeast Region, DED does not significantly affect lnCE (−0.027) or CI (0.177), but it has a positive, albeit not significant, impact on LCCE (0.077). The adjusted R-squared values are high for lnCE (0.903) but moderate for CI (0.559) and LCCE (0.497), indicating a reasonable fit for the models.

Table 7 explores the heterogeneous impacts of the digital economy on low-carbon city efficiency (LCCE) and carbon emissions across different city sizes, categorized into large cities and medium-sized and small cities. The table presents the effects of digital economy development (DED) on the logarithm of carbon emissions (lnCE), carbon intensity (CI), and LCCE. In large cities, the impact of DED on lnCE is negative (−0.038), but not statistically significant, indicating that the digital economy does not have a substantial effect on reducing carbon emissions in these areas. Similarly, the impact on CI is also negative (−0.004) and not significant, suggesting a limited influence on carbon intensity. However, DED shows a positive but non-significant effect on LCCE (0.021), indicating a potential, though not statistically confirmed, improvement in low-carbon efficiency. The adjusted R-squared values are high for lnCE (0.920), suggesting a robust model fit but moderate for CI (0.637) and LCCE (0.566). In contrast, medium-sized and small cities show a more pronounced impact. DED has a significant negative effect on lnCE (−0.073, $p < 0.10$), indicating that the digital economy significantly reduces carbon emissions in these cities. The effect on CI is negative (−0.052) but not statistically significant, suggesting some reduction in carbon intensity, though not confirmed by statistical significance. The impact on LCCE is positive and significant (0.030, $p < 0.10$), indicating that the digital economy effectively enhances low-carbon efficiency in medium-sized and small cities. The adjusted R-squared values are slightly lower for lnCE (0.858) compared to large cities but higher for CI (0.681) and moderate for LCCE (0.528), suggesting a reasonable fit for the models.

The impact of digital finance on LCC efficiency varies among city kinds of resources, as shown in Table 8. It explores the heterogeneous effects of digital economy development (DED) on carbon emissions and low-carbon city efficiency (LCCE) in resource-dependent and non-resource-dependent cities. The analysis reveals distinct differences in how these cities respond to the digital economy. In resource-dependent cities, DED has a significant negative impact on the logarithm of carbon emissions (lnCE) with a coefficient of −0.111, which is important at the 10% level and indicates a reduction in emissions. It also significantly reduces carbon intensity (CI) with a coefficient of −0.090,

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TABLE 6 Heterogeneous impacts rely on place of origin.

Variables	(1)	(2)	(3)
	lnCE	CI	LCCE
Eastern region			
DED	−0.076*	−0.023	0.022
	(−1.898)	(−0.764)	(1.018)
N	1,247	1,247	1,247
adj. R^2	0.929	0.546	0.579
Central region			
DED	−0.152**	−0.085**	0.062**
	(−2.453)	(−2.511)	(2.146)
N	1,189	1,189	1,189
adj. R^2	0.893	0.632	0.555
Western Region			
DED	−0.024	−0.075	−0.002
	(−0.509)	(−1.157)	(−0.074)
N	1,060	1,060	1,060
adj. R^2	0.878	0.695	0.455
Northeast Region			
DED	−0.027	0.177	0.077
	(−0.257)	(0.901)	(1.472)
N	482	482	482
adj. R^2	0.903	0.559	0.497
Controls	Yes	Yes	Yes
City FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

**, *indicates significance at the 5%, 10% level.

which is significant at the 5% level, suggesting that the digital economy effectively decreases the amount of carbon emissions per unit of GDP. Furthermore, DED positively affects LCCE with a coefficient of 0.054, which is significant at the 5% level and indicates improvements in low-carbon efficiency. The adjusted R-squared values are high for lnCE (0.867) and CI (0.766) and moderate for LCCE (0.487), suggesting the models explain a substantial portion of the variance in these outcomes. Conversely, in non-resource-dependent cities, the effects of DED on lnCE (−0.053) and CI (−0.023) are negative but not statistically significant, indicating that the digital economy's impact on reducing emissions and intensity is less pronounced in these areas. The effect on LCCE is positive (0.018) but also insignificant, suggesting limited improvements in low-carbon efficiency. The adjusted R-squared values are high for lnCE (0.928) and moderate for CI (0.612) and LCCE (0.569), indicating a good fit for the models.

The findings support both Hypothesis 1, 2. For Hypothesis 1, using a fixed-effect model effectively captures the impact of direct transfer mechanisms by controlling for unobserved heterogeneity across cities and periods, leading to statistically significant findings. The analysis demonstrates that the digital economy, represented by the Digital Economy Development (DED) index, significantly reduces carbon emissions and carbon intensity while improving low-carbon city efficiency (LCCE), as shown by the negative coefficients for carbon intensity and emissions and positive coefficients for LCCE. This confirms the fixed-effect model's ability to isolate the effects of the digital economy on these outcomes. For Hypothesis 2, the content reveals that the internet-based economy enhances LCC effectiveness and reduces greenhouse gas emissions by promoting innovations in green technologies. The study's mechanism analysis shows that the digital economy facilitates more efficient carbon management and promotes environmental sustainability through green technology innovation, evidenced by the significant positive impact of DED on LCCE and the reduction in carbon emissions and intensity. These findings confirm that the digital economy's advancements enhance low-carbon city effectiveness and reduce greenhouse gas emissions, aligning with the hypothesis.

6 Discussion

The role of the Internet as a new economic framework in reducing carbon emissions has been extensively examined by scholars, but their conclusions remain inconsistent. This study aims to explore the impact of the digital marketplace on the efficiency of low carbon consumption (LCC). Empirical investigations across various cities indicate that the digital economy is critical in reducing greenhouse gas emissions in city areas. Findings demonstrate an inverse relationship between the digital economy and greenhouse gas emissions. Specifically, for every one percentage point increase in digital business activity, there is an approximate 0.886% decrease in carbon emissions. Digitalization further contributes to reducing the overall magnitude of carbon emissions. In addition to lowering regional carbon dioxide levels, advancements in digital technologies also encourage neighboring cities to reduce their carbon emissions. The emerging digital economy thus enhances LCC efficiency, offering substantial potential for reducing greenhouse gases. However, contrary findings have been reported, suggesting that expanding the digital marketplace could increase greenhouse gas emissions and negatively impact environmental preservation. These discrepancies may be attributed to differences in indicators and sample compositions. Most studies have focused on national or provincial scales, utilizing isolated variables to examine the relationship between the digital marketplace and carbon emissions. As a result, it is crucial to assess LCC efficiency at the municipal level using a multidimensional output framework. The findings of this study offer a pathway for promoting sustainable development and achieving carbon neutrality by 2030.

The intermediary impact evaluation reveals that the digital economy primarily influences LCC effectiveness by fostering the development of green technologies. By replacing traditional methods with environmentally friendly alternatives, green technology development has the potential to reduce carbon dioxide emissions. Moreover, these innovations can enhance LCC efficiency by improving output and contributing to sustainable and inclusive growth. Integrating the digital economy with green technological innovation is essential for such development. Additionally, introducing digital currencies can indirectly reduce carbon emissions by developing green technologies. Further research into the effects of the internet-based economy on LCC effectiveness indicates that these effects vary according to city size, location, and the nature of commodities. During the data collection period, it was observed that the digital marketplace had little to no impact on reducing carbon emissions in northern and western regions, while it significantly improved LCC outcomes in central and eastern cities. This disparity may be explained by the more decisive influence of digital finance in the latter regions, which benefit from higher internet

TABLE 7 Heterogeneous impacts from different-sized cities.

Variables	Large cities			Medium-sized and small cities		
	(1)	(2)	(3)	(4)	(5)	(6)
	lnCE	CI	LCCE	lnCE	CI	LCCE
DED	−0.038	−0.004	0.021	−0.073*	−0.052	0.030*
	(−1.265)	(−0.137)	(0.978)	(−1.782)	(−1.211)	(1.782)
N	1,437	1,437	1,437	2,541	2,541	2,541
adj. R^2	0.920	0.637	0.566	0.858	0.681	0.528
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

*indicates significance at the 10% level.

TABLE 8 Heterogeneous outcomes depending on available resources.

Variables	Resource dependent cities			Non-resource dependent cities		
	(1)	(2)	(3)	(4)	(5)	(6)
	lnCE	CI	LCCE	lnCE	CI	LCCE
DED	−0.111***	−0.090***	0.054***	−0.053***	−0.023***	0.018***
	(−2.975)	(−3.001)	(2.511)	(−2.611)	(−3.814)	(2.023)
N	1,657	1,657	1,657	2,321	2,321	2,321
adj. R^2	0.867	0.766	0.487	0.928	0.612	0.569
Controls	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes

***indicates significance at the 1% level.

usage rates and more advanced digital networks. Despite benefiting from national policies, the digital marketplace in central and eastern China struggles to significantly reduce greenhouse gas emissions due to weaker economies and outdated digital infrastructures.

Moreover, while the digital economy does not significantly affect LCC efficiency in large cities, it has been found to substantially reduce carbon emissions and improve LCC productivity in smaller and medium-sized towns. Large city centers have benefited from reduced carbon emissions by adopting advanced technologies such as artificial intelligence and satellite imaging in manufacturing and daily life. In contrast, smaller cities lag in technological innovation and energy efficiency. By adopting digital technologies, smaller cities can enhance LCC effectiveness and promote high-tech innovation, leading to more efficient energy consumption and reduced greenhouse gases. The practical implications of this study on the digital economy's impact on carbon emissions and sustainability are profound, offering actionable insights for policymakers, businesses, and city planners. Firstly, the research highlights the critical role of integrating digital technologies with environmental policies to maximize their benefits in reducing carbon emissions. Policymakers are encouraged to develop regulatory frameworks that incentivize the adoption of eco-friendly digital solutions and raise public awareness about sustainable practices. This involves setting clear standards and providing financial incentives for businesses to adopt green technologies, which can lead to more efficient resource use and significant reductions in emissions. Furthermore, investing in digital infrastructure and supporting research and development in green technologies are essential to create an enabling environment for sustainable innovation. By aligning digital economy strategies with environmental goals, governments can ensure that technological advancements contribute positively to long-term sustainability objectives. Secondly, the study underscores the importance of tailoring digital economy strategies to regional contexts, given the observed heterogeneity in its impact on carbon emissions. Local governments should adopt strategies that consider specific regional conditions, such as the level of digital infrastructure development and predominant industrial activities. For instance, regions with advanced digital infrastructure might focus on integrating digital solutions to enhance energy efficiency and reduce emissions in manufacturing processes.

Conversely, areas with less developed digital economies could prioritize innovations in green technology and smart city initiatives to foster sustainable city development. By adopting region-specific strategies, policymakers can better harness the digital economy's potential to drive sustainable growth and reduce carbon emissions, ensuring that the benefits are equitably distributed across different geographic areas. Additionally, businesses are encouraged to integrate digital technologies into their operations to improve environmental efficiency and competitiveness, leveraging the power of digital platforms to facilitate information exchange, collaboration, and innovation across sectors. These practical implications provide a roadmap for stakeholders to leverage the digital economy to promote sustainable growth and reduce carbon footprints, thereby contributing to the broader discourse on environmental sustainability in digital transformation.

Lastly, while the digital market may have a limited impact on LCC outcomes in resource-dependent cities, it holds the potential to lower their carbon footprint significantly. When per capita GDP is considered, there is no significant negative correlation between environmental availability and economic development. Although resource-based cities may lag behind non-resource-based cities in establishing digital networks, emerging digital technologies, such as big data, have the potential to accelerate the development of environmentally friendly products and optimize energy usage. Consequently, resource-dependent cities can leverage digital technologies to improve LCC outcomes, overcome the "resource curse," and create new city advantages.

7 Conclusions and implications

The study investigates the role of the Internet of Things (IoT) in improving the efficiency of low-carbon cities by analyzing multiple outcomes, including greenhouse gas emissions, emission intensity, and metropolitan sustainability. Using survey data from 271 Chinese cities between 2010 and 2024, the research develops a comprehensive digital economy index to construct a multivariate production index for evaluating low-carbon city efficiency. Through fixed-effects modeling and mediation analysis, the study assesses the influence of the internet-driven economy on low-carbon city performance. The results demonstrate two main effects of the digital economy: at the national level, it reduces greenhouse gas emissions and emission intensity while enhancing the operational efficiency of low-carbon cities. Moreover, the study emphasizes that green technology innovation serves as a key pathway through which the digital economy lowers carbon emissions and intensity, thereby boosting the productivity of low-carbon communities.

The impact of the internet-based economy on low-carbon city efficiency (LCCE) exhibits notable geographic variation, with more substantial effects observed in central and eastern cities. In terms of city size, the digital economy exerts a stronger influence on small and medium-sized cities, contributing to reduced carbon dioxide emissions and improved LCCE. In contrast, the effect is less pronounced in resource-dependent cities, indicating that local resource endowments shape the effectiveness of digital initiatives in advancing urban sustainability.

The theoretical implications of this research are multifaceted and contribute significantly to the literature on digital transformation and environmental sustainability. First, the study underscores the transformative potential of the digital economy in mitigating greenhouse gas emissions and advancing urban sustainability. By integrating IoT, artificial intelligence, and big data analytics, cities can optimize energy consumption, enhance environmental monitoring, and spur green innovation. This supports the broader theoretical proposition that digitalization acts as a catalyst for sustainable development by reshaping conventional economic and ecological systems. Second, the findings highlight the importance of accounting for regional heterogeneity, as the environmental benefits of the digital economy are more evident in central and eastern regions—a disparity likely driven by variations in digital infrastructure, economic development, and policy support. This suggests that region-specific strategies are essential to maximize the digital economy's positive impact. Third, the study advances theoretical understanding by identifying key mechanisms, such as green technology innovation and industrial restructuring, that mediate the relationship between digitalization and environmental outcomes. Finally, the research offers a nuanced perspective on how city size and resource dependency moderate the effectiveness of digital economy initiatives, underscoring the need for tailored policy approaches in diverse urban contexts.

The managerial implications of the study on the digital economy's impact on low-carbon city efficiency are significant for policymakers, city planners, and business leaders. The findings suggest integrating digital technologies into city management can significantly enhance environmental sustainability. Managers and policymakers should prioritize investments in digital infrastructure, such as IoT and smart city technologies, to optimize energy use and reduce carbon emissions. This strategic focus can lead to more efficient city systems and contribute to achieving broader sustainability goals. Secondly, the study highlights the importance of regional and city-specific strategies. Given the varying impacts of the digital economy across different regions and city sizes, managers should tailor their approaches to local contexts. For instance, central and eastern areas may benefit more from digital economy initiatives, suggesting that resources and efforts should be concentrated in these areas to maximize environmental benefits.

Similarly, smaller and medium-sized cities might require strategies different from those of larger city centers to effectively leverage digital technologies for sustainability. Thirdly, the role of green technology innovation as a mediating factor underscores the need for businesses to invest in research and development. Companies should focus on developing and adopting green technologies to enhance operational efficiency and reduce environmental impact. This approach aligns with sustainability objectives and offers competitive advantages in an increasingly eco-conscious market. Furthermore, the study suggests that resource-dependent cities can significantly benefit from digital economy initiatives. Managers in these areas should leverage digital tools to improve resource management and reduce emissions. This could involve adopting digital platforms for monitoring and optimizing resource use and integrating digital solutions into existing industrial processes. Finally, the research indicates that the digital economy can be crucial in shaping policy frameworks for sustainable city development. Policymakers should consider incorporating digital economy metrics into environmental regulations and city planning processes. This integration can help create more resilient and adaptive city environments that are better equipped to meet the challenges of climate change and resource scarcity.

Several avenues for future research can be identified based on the current research landscape and findings regarding the digital economy's impact on low-carbon city efficiency and carbon emissions. One area of exploration is the regional disparities in the effects of the digital economy. Future studies could investigate why certain regions, such as central and eastern areas, benefit more from digital economy initiatives than others, considering regional policies, infrastructure, and economic conditions. Understanding these differences could provide insights into optimizing digital economy strategies across diverse geographic areas. Another promising research direction is sector-specific analysis. While existing research often focuses on broad impacts, there is a need to understand how different industries within the digital economy contribute to carbon reduction. Future research could examine the effects of digital transformation in sectors such as manufacturing, transportation, and agriculture, identifying the best practices and technologies that lead to significant environmental benefits.

Additionally, integrating emerging technologies like artificial intelligence, blockchain, and advanced IoT in enhancing the digital economy's impact on sustainability should be further explored. Research could focus on how these technologies can be integrated into existing digital frameworks to optimize resource use, reduce emissions, and improve city sustainability. Longitudinal studies are also needed to track the evolution of the digital economy and its long-term impacts on carbon emissions and city sustainability. Such studies could provide valuable data on trends, enabling better forecasting and strategic planning for sustainable city development. Furthermore, future research could focus on developing comprehensive policy and governance frameworks that support the digital economy's role in achieving carbon neutrality. This includes examining how government policies can facilitate digital transformation in traditional industries and promote green innovation. The socio-economic implications of digital transformation, such as changes in employment patterns, income distribution, and city-rural divides, also warrant further investigation. Understanding these impacts can help design inclusive policies that ensure equitable benefits from the digital economy's growth. Lastly, conducting cross-country comparative studies can provide insights into how various national contexts influence the digital economy's effectiveness in reducing carbon emissions. Research could identify the best global practices and inform international policymaking. By addressing these areas, future research can deepen our understanding of the digital economy's potential to drive sustainable development and inform strategies to maximize its positive impact on the environment and society.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WH: Supervision, Visualization, Writing – review & editing. JZ: Data curation, Formal analysis, Methodology, Writing – original draft. XL: Methodology, Software, Writing – original draft.

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Conflict of interest

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