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Research article

Digital economy and fiscal decentralization: Drivers of green innovation in China

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ABSTRACT

The impact of government behavior under a fiscal decentralization system on the interplay between the digital economy and both the quality and efficiency of green innovation poses an intriguing question. To address this, the present study employs two-way fixed-effects models, instrumental variables, and spatial econometric techniques, using data from 30 provinces and cities in China spanning 2004 to 2019. The findings reveal that the advancement of the digital economy significantly enhances the quality and efficiency of green innovation. In the context of China's fiscal decentralization, local governments frequently employ a "race to the top" strategy, amplifying the digital economy's beneficial impact on green innovation. This effect is particularly pronounced in economically prosperous regions that prioritize environmental assessments. Additionally, the study identifies a spatial demonstration effect, indicating that fiscal decentralization bolsters the digital economy's influence in adjacent regions. Consequently, policy recommendations include deepening the digital economy, advocating for increased fiscal autonomy for local governments, refining the performance appraisal systems for local officials, and establishing a well-calibrated environmental transfer mechanism. Further, leveraging the positive spatial correlations among local governments can foster a competitive yet collaborative landscape for green innovation.

1. Introduction

Green Innovation, a key driver of global sustainable development, has become increasingly important, especially due to escalating climate challenges [1,2]. Under the auspices of global low-carbon development strategies, countries have increased their R&D efforts in green innovation, with China's surge in green innovations being particularly notable [3]. However, despite these efforts, the anticipated shift towards a low-carbon economy and societal model in China has yet to fully materialize [4]. The growth in green innovation measures, predominantly gauged by the volume of patents, led to the emergence of "patent bubbles." Such trends, often stimulated by government subsidies and regulatory mandates, may not reflect true innovation, potentially obscuring authentic progress towards green and low-carbon development [5]. This situation necessitates the reassessment of green innovation, placing a stronger emphasis on its quality and efficiency rather than sheer quantity.

Concurrently, academics have widely acknowledged the digital economy as a green economy and its important contribution to

Abbreviations: DE, Digital Economy; FD, Fiscal Decentralization; GIQ, Green Innovation Quality; GIE, Green Innovation Efficiency.

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green innovation [6]. Digital economy disrupts the conventional linear model of innovation with its extensive innovative capacity, breadth, and depth [2], enhancing the innovation landscape, and consequently fostering higher-quality green innovation [7]. Moreover, digital economy facilitates the reduction of information acquisition and exchange costs by overcoming spatial and temporal barriers, thereby significantly enhancing green innovation efficiency [8].

Nevertheless, there are concerns about the "green paradox", which suggests that the development of digital economy could hinder innovation momentum and lead to a "low-end trap" in technological progress [9]. This trap can escalate the costs of green innovation owing to imbalanced resource allocation, long-term investments, and high sunk costs, ultimately diminishing the quality of green innovation output [10]. Furthermore, the data-driven nature of the digital economy can lead to "information overload," negatively impacting decision-making processes and, consequently, green innovation efficiency [11]. However, the cumulative effect of the digital economy on both the quality and efficiency of green innovation remains underexplored, indicating a gap in the literature that warrants further investigation.

Furthermore, while studies have explored the intrinsic link between digital economy and green innovation [12], the external effects of government behavior have not been entirely considered. Unlike conventional innovation paradigms, green innovation is characterized by "double externalities," comprising technological spillovers and environmental repercussions via cost mitigation [13]. This duality attenuates incentives for green R&D within the societal fabric, inadvertently fostering reliance on antiquated, environmentally detrimental technologies. This underscores the essential role of government intervention [14]. As a globally recognized policy measure, fiscal decentralization (FD) involves the transfer of spending authority, taxation, and responsibility from central to lower levels of government [15]. In federal systems, the concept of "voting with one's feet" suggests that local governments can align policies more closely with resident preferences [16]. Thus, fiscal decentralization is beneficial for enhancing environmental sustainability and promoting green innovation [17].

However, in China's unique political and economic context, the simultaneous existence of political centralization and economic decentralization has brought controversy to previously understood mechanisms [18,19]. Fiscal decentralization in China refers to the delegation of fiscal responsibilities from the central government to local governments, allowing regions to have greater control over their revenue and expenditures [20,21]. The central government's approach to appointing local officials fuels competition among regions, and this competitive uncertainty influences local fiscal and policy choices [22]. Some researchers argue that China's fiscal decentralization prioritizes economic growth, potentially leading local governments to lower environmental standards in a "race to the bottom." This scenario occurs when local governments compete to attract investment by reducing regulatory standards, thereby undermining environmental conservation [23]. Conversely, another perspective suggests that fiscal decentralization may encourage local governments to prioritize environmental issues and foster sustainability through a "race to the top." In this case, local governments compete to improve environmental standards, aiming to attract green investments and enhance their reputation [15]. Whether it's a "race to the bottom" or "race to the top" one—local government strategies profoundly influence the interplay between the digital economy and green innovation. However, most research to date has explored the effects of the digital economy and fiscal decentralization on green innovation separately [24], paying little attention to a holistic examination of these three variables.

In summary, this study aims to explore the following key questions: Can the digital economy simultaneously enhance the quality and efficiency of green innovation? If so, under China's unique system of fiscal decentralization, will it amplify the positive effects of the digital economy, or will it undermine these benefits? Additionally, does this impact exhibit heterogeneity across different environmental performance assessments and levels of economic development? How do these results change when spatial factors are taken into account? To investigate these issues thoroughly, we collected relevant data from 30 provinces in China from 2004 to 2019, employing two-way fixed effects, endogenous instrumental variables, and spatial econometric models to understand the mechanisms through which the digital economy impacts green innovation comprehensively.

Compared with existing studies, the contributions of this research are manifested in three main areas. First, previous studies have typically focused only on the singular relationships between digital economy, fiscal decentralization, and green innovation. This study innovatively integrates digital economy, fiscal decentralization, and green innovation into the same theoretical framework and conducts a comprehensive analysis of the quality and efficiency dimensions of green innovation. This expands on the related research by Dou and Gao (2022) [11] and Li and Wang (2023) [25]. Second, although the literature has explored the positive impact of fiscal decentralization on green innovation [26], this study further investigates the boundary effects of fiscal decentralization. It analyzes the heterogeneity in effects from the dual perspectives of environmental performance assessments and economic development, providing new theoretical insights for the evolution of fiscal decentralization theory; Lastly, this study innovatively introduces a spatial perspective, assessing the impact of fiscal decentralization on the relationship between the digital economy and green innovation across different geographic spaces—an aspect not previously covered in existing studies. Through this approach, the research not only enriches the academic discussion on digital economy, decentralization and green innovation, but also provides empirical support for policymaking from a spatial perspective.

The remainder of this study is structured as follows: Section 2 presents the theoretical analysis and establishes the research hypotheses. Section 3 elaborates on the construction of the model, methodology employed, and data sources and processing. Section 4 presents the results of the empirical analysis of digital economy's impact on the quality and efficiency of green innovation and discusses these findings. Section 5 discusses the effects of fiscal decentralization on green innovation. Section 6 presents the principal conclusions of the study and explores policy implications and limitations of the findings.

2. Theoretical analysis and research hypothesis

2.1. Digital economy, green innovation quality, and efficiency

Digital economy is an evolving economic model that plays a pivotal role in advancing green innovation through externalities and economies [27]. It employs advanced technologies, such as data analytics and cloud computing, to bolster R&D in green innovation [28]. Moreover, by enabling the widespread dissemination of knowledge and hastening technological progress, digital economy has emerged as a formidable catalyst for green innovation [12]. However, simply increasing the amount of green innovation is insufficient for sustainable development and there is an urgent need to improve the quality and efficiency of these innovations. Therefore, this study examines the impact of digital economy on the quality and efficiency of green innovation and elucidates its potential to promote a sustainable future.

Digital economy influences green innovation quality (GIQ) in multiple ways. Digital economy has enabled using digital technologies such as big data, cloud computing, and artificial intelligence. These technologies can reduce information asymmetry, which hinders innovation practices [29]. By making information more transparent, they can improve market efficiency and promote the diffusion of green and low-carbon concepts [30]. This can stimulate regional green innovation activity and enhance quality. Digital economy has also improved government regulatory mechanisms through the widespread use of digital platforms [31]. This can help governments regulate innovative behavior more effectively [32]. Consequently, innovative organizations are more likely to introduce green products and services that have real impacts than symbolic innovations that only aim to gain policy or market advantages [33]. Moreover, digital economy facilitates a fast flow of knowledge and technology, which challenges the linear innovation model of knowledge accumulation for applications [34]. This provides strong support for the improvement of GIQ.

The green innovation efficiency (GIE) can be examined from two angles. First, digital economy growth significantly boosts the frequency of green innovation, broadens its scope, and refines the production process. This enhancement improves industrial productivity and responsiveness [35] and avoids inefficiencies and unnecessary waste in green innovation resource allocation by expanding information access [36]. Second, the digital economy's innovative digital technologies facilitate the smart transformation of innovation and production processes [28]. This transformation increases innovation and energy usage efficiency [37]. Furthermore, some researchers have analyzed the impact of digital economy on GIE through the lens of energy efficiency. They argued that innovative technologies in digital economy could enhance energy efficiency [38], leading to low-carbon, efficient, and safe green outputs, thereby improving GIE.

In conclusion, this study aims to confirm the relationship between digital economy and gains in green innovation quality and efficiency. Based on this discussion, we propose the following hypothesis.

Hypothesis 1. The digital economy promotes green innovation quality and efficiency simultaneously.

2.2. Synergy effects of fiscal decentralization

The analysis presented in the previous section unequivocally demonstrates that green innovation is characterized by a dual externality, necessitating intervention from governmental bodies. Consequently, initiatives undertaken by local governments are instrumental in defining the dynamics between digital economy and green innovation. The strategic choices made by these local authorities—whether to embark on a "race to the top" by fostering innovation and environmental sustainability, or to pursue a "race to the bottom," prioritizing immediate economic benefits—significantly impact how digital economy catalyzes green innovation.

Fiscal decentralization (FD), described as a strategy for providing economic incentives to local governments for revenue generation and investment in economic development [39], plays a pivotal role in influencing these strategic decisions. Many researchers maintain that decentralized governments, with their informational edge, display greater adaptability to citizens" needs and preferences of citizens [26,40]. Typically, these governments proactively increase citizen welfare and augment investments in environmentally friendly initiatives [19]. In the Chinese context, the coexistence of "political centralization and economic decentralization" complicates the scenario. It tends to undermine the "vote with your feet" mechanism [15]. However, research indicates that local government behavior in China still aligns, to some extent, with public preferences, although these are not always the primary policy focus. Other scholars have corroborated that Chinese local governments heed public calls for green development under fiscal decentralization [41,42]. Additionally, the advent of sustainability strategies has spurred local governments in China to engage in a "race to the top." This strategy aims to incentivize innovative organizations to pursue green innovation. They do so by offering financial subsidies and imposing strict environmental regulations [43,44]. In summary, we propose that a specific fiscal decentralization model in China amplifies the impact of digital economy on regional green innovation.

In view of this, the following hypotheses are proposed.

Hypothesis 2a. The digital economy and fiscal decentralization work synergistically to improve the quality and efficiency of green innovation.

Concurrently, it is crucial to emphasize that the option of "race to the top" or "race to the bottom" is not a fixed choice for local governments once they secure greater financial autonomy. This decision is influenced by environmental assessment pressures and the economic development [45,46]. Using GDP as the principal metric for assessing local cadres, fiscal decentralization incentivizes these governments to prioritize economic advancement, often at environmental expense. Consequently, resources are frequently allocated to public services and infrastructure initiatives that fuel rapid economic growth [47]. However, this trend has changed since 2007.

China's *Eleventh Five-Year Plan* incorporated ecological and green development criteria into performance evaluations of local governments [48], reinforcing their primary responsibility for environmental protection. Furthermore, the stages of economic development in various economies shape the environmental preferences of local governments. The Environmental Kuznets Curve (EKC) indicates an inverted U-shaped relationship between environmental pollution and per capita income [49]. As economies mature, the financial pressures on local governments ease, making them more inclined to allocate finances towards environmental governance to stimulate GI [50]. Therefore, this study discusses the heterogeneity of the impacts of digital economy and fiscal decentralization on green innovation in terms of vertical performance appraisal adjustment and the horizontal degree of economic development. The inclusion of environmental performance assessments amplified the synergistic effects of fiscal decentralization and digital economy. Furthermore, these synergistic effects are notably strengthened in regions characterized by high economic development.

The following hypotheses are proposed.

Hypothesis 2b. The inclusion of environmental factors in performance assessments amplifies the synergistic effect between the digital economy and fiscal decentralization.

Hypothesis 2c. In regions with advanced economic development, the synergistic impact of the digital economy and fiscal decentralization become more pronounced.

Furthermore, both digital economy and green innovation exhibit marked spillover effects [28], and significant strategic interactions occur among local governments in their approach to GI. Therefore, the synergistic effects of digital economy and fiscal decentralization on green innovation warrant consideration regarding neighborhood effects. As seen through the demonstration warning effect, a heightened focus on environmental governance in local performance assessments inevitably sparks competitive interactions among local governments [51]. This competition fosters an institutional environment favorable for green innovation and cultivates a healthy competitive ethos of "striving for excellence" [52]. Such an environment also incentivizes "lagging" regions to leverage successful practices and emerging technological opportunities to enhance green innovation [53]. Given these dynamics, we posit that the interplay between digital economy and fiscal decentralization generates a positive spatial spillover effect, elevating the quality and efficiency of GI across regions.

In summary, we propose the following hypotheses.

Hypothesis 2d. The interplay between digital economy and fiscal decentralization produces a positive spatial spillover effect, improving the quality and efficiency of green innovation across regions.

The analysis of the mechanism in this study is illustrated in Fig. 1.

3. Research design

3.1. Model design

To test the impact of the digital economy (DE) on the quality and efficiency of green innovation, we referred Gai et al. (2022) [54] and established a baseline regression model, as shown in Equation (1):

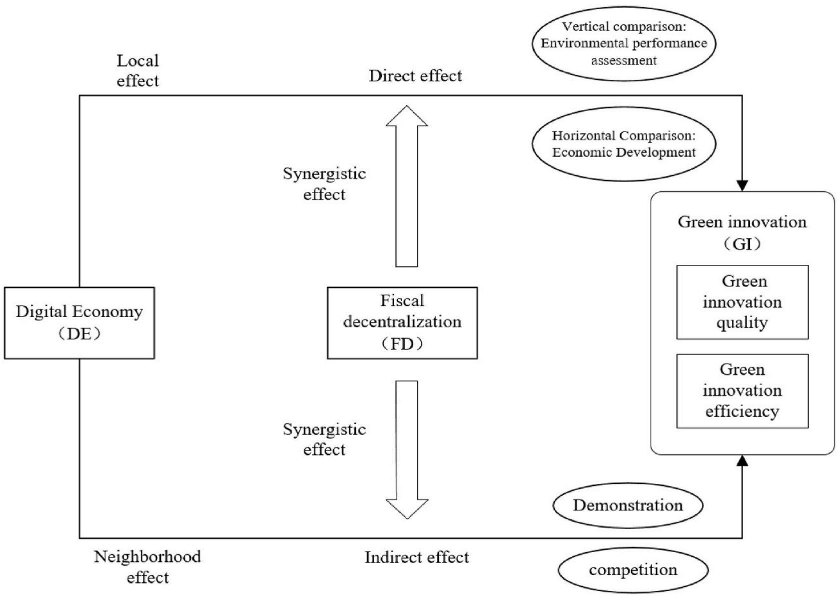


Fig. 1. Diagram showing the Mechanism Analysis Framework.

$$Y_{it} = \beta_0 + \beta_1 DE_{it} + \beta_c X_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{1}$$

In Equation (1), the indices i and t denote individual provinces and years, respectively. Y_{it} represents the dependent variable: the quality and efficiency of green innovation. $DE_i t$ signifies the level of digital economy advancement, X_{it} includes a set of control variables, μ_i and φ_t represent fixed effects for individuals and time, respectively, and ε_{it} is the error term.

To further examine the influence of government actions on the relationship between the digital economy and the quality and efficiency of green innovation, we adopt the approach used by Wang et al. (2022) [55]. We introduce fiscal decentralization and the interaction term between digital economy and fiscal decentralization ($DE_{it} * FD_{it}$), as shown in Equation (2):

$$Y_{it} = \beta_0 + \beta_1 DE_{it} + \beta_2 FD_{it} + \beta_3 DE_{it} * FD_{it} + \beta_c X_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{2}$$

Here, we focus on the interaction term $DE_{it} * FD_{it}$. A notably positive coefficient for this term implies that digital economy bolsters green innovation in provinces with heightened fiscal decentralization. This coefficient resembles the difference-in-differences methodology, offering some insight into causal relationships among variables [56,57].

Furthermore, this study explores the spatial spillover effects of digital economy and fiscal decentralization on green innovation. To capture these effects, we follow the methodologies of existing research [58,59] and incorporate the spatial interaction terms of the digital economy, fiscal decentralization, and other relevant variables into Equation (2). This expansion allowed us to extend the model within the framework of spatial econometrics, as shown in Equation (3).

$$Y_{it} = \beta_0 + \lambda WY_{it} + \beta_1 DE_{it} + \beta_2 FD_{it} + \beta_3 DE_{it} * FD_{it} + \beta_c X_{it} + \delta_1 WDE_{it} + \delta_2 WFD_{it} + \delta_3 WDE_{it} * FD_{it} + \delta_c WX_{it} + \mu_i + \varphi_t + \varepsilon_{it} \tag{3}$$

In Equation (3), W represents the spatial weight matrix, which is constructed using either a binary adjacency matrix or a geographic distance weight matrix [60]. The adjacency matrix W_{ij}^A captures the binary neighborhood relationship between geographical units, assigning a value of one if two units are adjacent and zero otherwise [61]. Alternatively, the distance matrix W_{ij}^D is constructed based on the actual geographic distances between units, reflecting their spatial proximity, with matrix elements typically defined by an inverse distance function or other measures of spatial distance [62]. WDE_{it} denotes the spatial lag of DE, and WFD_{it} represents the spatial lag of FD. The interaction term $WDE_{it} * FD_{it}$ is the spatial lag of the interaction between DE and FD. WX_{it} reflects the spatial lag of the control variables. All other variables were consistent with previous definitions.

3.2. Selection of variables

3.2.1. Digital economy

The measurement of digital economy has become a focal point in both academic inquiry and policy formulation. Leading international organizations, such as the OECD, Eurostat, and the World Bank, have established frameworks and indicators for assessing digital economy [63]. However, applying these frameworks to the Chinese context reveals adaptive differences owing to geographical and cultural factors. Moreover, Chinese scholars have developed localized indicators, primarily focusing on Internet development and digital finance [7]. However, data accessibility challenges have limited most of these studies to regional analyses after 2011.

Digital economy is an economic system that leverages information and communication technology (ICT) infrastructure to support various information activities [64]. This infrastructure forms the foundation of the digital economy and facilitates the dissemination and application of digital information [65]. The scale of development indicates the reach and influence of digital economy's core business, whereas the degree of application measures the extent and depth of digital technology usage across economic sectors [66].

Here, we focused on these three core elements to develop an evaluation framework for digital economy. The entropy value method was employed for the measurement. Specifically, we consider digital economy infrastructure as the cornerstone of development, using indicators such as fiber-optic cable length per square kilometer, mobile telephone exchange capacity per household, and broadband access ports per 100 people [67]. To gauge the scale of development, we examined the total volume of telecommunications services, number of cell phone users, and express parcel volume. These metrics were selected from sectors closely linked to digital economy, such as telecommunications and express delivery. Finally, to assess the degree of application, broader economic and societal factors were considered. These include the workforce for information transmission, software, and information technology services; the proportion of mobile Internet users; and overall Internet penetration rates [68].

3.2.2. Green innovation: quality and efficiency

Defined as innovative activities that concurrently yield economic and environmental advantages, green innovation has been attracting increasing attention from the global academic community. Previous studies have often measured regional green innovation using patent applications [7]. However, this metric does not adequately capture the complete scope of regional green innovation. Moreover, green innovation goes beyond technological expansion or product counting. It centers on creating substantial societal value while ensuring resource efficiency and minimizing environmental degradation during the innovation process [69,70]. Accordingly, this study examined the interplay between digital economy and green innovation, focusing on both the quality and efficiency dimensions.

To assess green innovation quality (GIQ), we considered the Chinese context, in which utility and appearance patents often align with policy objectives to secure governmental support. In contrast, invention patents signify higher-quality innovations. Drawing on the works of Aghion et al. [71] and Rao et al. [72], we employ the number of green invention patent applications per 10,000 people as a critical measure for assessing GIQ.

Regarding GIE, we employed the super-efficient SBM model for estimation [73]. Referencing Zeng et al. (2021) [74] and Li et al. (2023) [28], our analytical framework incorporated resource-environmental factors. Specifically, we used the R&D internal economy, full-time equivalents of R&D personnel, and energy consumption as inputs for capital, labor, and resources, respectively. As for output variables, we followed Fan et al. (2021) [75] and included the number of green patent applications and new product sales as the desired outputs. We also considered industrial wastewater, solid waste emissions, and sulfur dioxide emissions as undesirable outputs. Given the challenge of directly measuring green innovation inputs, we used R&D inputs as a proxy, acknowledging the potential bias. To enhance robustness, we supplemented our analysis with provincial patent application data as a key GIE metric.

The method for calculating regional GIE in China proposed by Wu and Fan [76] is defined as Equations (4) and (5):

$$\rho^* = \min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}}{x_{ik}}}{\frac{1}{r_1+r_2}\left(\sum_{s=1}^{r_1}\frac{\bar{y}}{y_{sk}}+\sum_{q=1}^{r_2}\frac{\bar{b}}{b_{qk}}\right)} \tag{4}$$

$$\text{s.t.}\begin{cases} \bar{x} \geq \sum_{j=1,\neq k}^{n} \lambda_j x_{ij}, i = 1,\dots,m \\ \bar{y} \leq \sum_{j=1,\neq k}^{n} \lambda_j y_{sj}, s = 1,\dots,r_1 \\ \bar{b} \geq \sum_{j=1,\neq k}^{n} \lambda_j b_{qj}, q = 1,\dots,r_2 \\ \lambda_j > 0, \sum_{j=1,\neq k}^{n} \lambda_j = 1, \bar{x} \geq x_k, \bar{y} \leq y_k, \bar{b} \geq b_k \end{cases} \tag{5}$$

In Equations (4) and (5), the measure of Green Innovation Efficiency (GIE) for a province, denoted by ρ^*, indicates higher efficiency with larger values. The variable $\bar{x}$ refers to the weighted average of all input values across decision units, while $\bar{y}$ denotes the weighted average of desired outputs, and $\bar{b}$ signifies the weighted average of non-desired outputs. Each decision unit is characterized by m inputs x_{ij}, where x_{ij} indicates the i - th type of resource in the j -th decision unit. These inputs yield r_1 desired outputs y_{sj}, representing the s-th desired outcome in the j-th decision unit, and non-desired outputs b_{qj}, representing the q-th non-desired outcome in the j-th decision unit. The weight vector λ_j is assigned to each decision unit to reflect its relative importance in the overall efficiency calculation. The number of input variables is m, the number of desired output variables is r_1, and the number of non-desired output variables is r_2.

3.2.3. Fiscal decentralization

Fiscal Decentralization refers to the central government empowering local governments in debt arrangements, tax management, and budget implementation [15]. The concept of fiscal decentralization lacks a consensus measure, but most researchers approach it through the lens of government revenue and expenditure [77,78]. Regarding China's distinct fiscal practices, many transfer indicators from higher-level governments have predefined uses that limit local autonomy. The essence of fiscal decentralization in China revolves around the allocation of tax revenues among different levels of government, commonly known as revenue decentralization [16]. Therefore, this study focuses on fiscal revenue decentralization. Following the methodologies of Eyraud & Lusinyan (2013) [79], we employed the ratio of provincial budget revenue to the sum of provincial and central budget revenue as our measure of the fiscal decentralization index.

3.2.4. Control variables

To rigorously evaluate the influence of digital economy on green innovation in terms of "quality enhancement and efficiency improvement," we controlled several key variables that could affect green innovation. These include the urbanization rate (URB), marketization (MAR), financial development (FIN), opening-up (OPEN), and infrastructure construction (INF).

(1) Urbanization rate (URB): The urbanization rate is usually accompanied by brain circulation and knowledge diffusion, which impacts green innovation. This study measures the urbanization rate through the proportion of urban population to the total population [73]. (2) Marketization (MAR): Marketization is the process of transitioning to a market economy. An increase in the degree of marketization enhances resource allocation efficiency and strengthens regional green innovation capabilities [80]. The China Marketization Index, developed by Fan et al. (2003) [81], has been widely used to measure the progress of market reforms across Chinese provinces [82,83]. Consequently, this study also employs the China Marketization Index to assess the degree of marketization. (3) Financial development (FIN): The improvement in the level of financial development is conducive to providing the necessary financial support for green innovation, which is expressed as the ratio of the loan balance of financial institutions to GDP [84]. (4) Opening-up (OPEN): Opening-up refers to the extent to which a region is open to international trade and investment [85]. This openness facilitates the acquisition of advanced green technologies and management practices. Advanced green technology and management experience, which in turn promotes green innovation, which we expressed through the ratio of total imports and exports to GDP [86]; (5) infrastructure construction (INF): Good infrastructure is conducive to the promotion and application of green technology, which is assessed in this study through the number of mileages of graded roads per square kilometer [87].

To ensure data integrity and analytical robustness, our empirical analysis employed a panel of 30 Chinese provinces, excluding

Tibet, Hong Kong, Macao, and Taiwan. The Internet is fundamental to the development of the digital economy [88]. The tenth anniversary of China's access to the international Internet in 2004 marked the onset of rapid Internet development [89]. Therefore, we designated the period from 2004 to 2019 as the study period. We chose this timeframe to avoid data inconsistencies introduced by the COVID-19 pandemic post-2019. The primary data sources included the *China Energy Statistical Yearbook*, *China Statistical Yearbook*, *China Environmental Yearbook*, and *China Science and Technology Statistical Yearbook*. We used STATA 17 (StataCorp LLC., College Station, TX, USA) for data analysis and generating graphs, and Origin 2018 (OriginLab Corp., Northampton, MA, USA) for generating graphs and performing statistical analysis. We applied logarithmic transformations to non-proportional data to facilitate analysis and used interpolation to address any missing data points. Table 1 presents the descriptive statistics of the main study variables.

3.2.5. Characterization facts

After calculating and obtaining the digital economy and green innovation data, we first compared the kernel density distributions of GIQ and GIE in each province between the high and low levels of digital economy development to visualize the correlation between digital economy and green innovation. As depicted in Fig. 2, we categorized the Chinese provinces into two groups, a high digital economy group (Group 1) and a low digital economy group (Group 0), based on the 75th and 25th percentiles of digital economy levels, respectively. Fig. 2a presents a kernel density comparison for GIE, and Fig. 2b does the same for GIQ. Notably, the kernel density distribution for the high-digital economy group exhibited a rightward shift in both green innovation efficiency and quality. This pattern suggests a positive correlation between elevated levels of digital economy development and enhanced green innovation performance in the Chinese provinces. This stylized fact provides preliminary evidence for the theoretical analysis conducted in this study, suggesting that digital economy may improve the quality and efficiency of green innovation to some extent.

4. Empirical analysis

4.1. The "quality enhancement and efficiency improvement" effects of the digital economy on green innovation

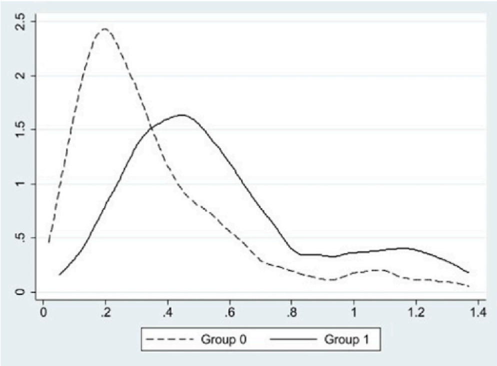
Table 2 provides empirical evidence that digital economy enhances both the quality and the efficiency of green innovation. Specifically, Columns (1) and (3) reveal the influence of digital economy on GIQ, whereas Columns (2) and (4) highlight their impact on GIE. The data in columns (1)–(4) show that digital economy significantly boosts GIQ and GIE irrespective of including control variables, thereby supporting **Hypothesis** 1. These findings align with those of Rao et al. (2022) [72], who found that digital finance positively affects the quantity and quality of green innovation at the organizational level. Our analysis extends these insights by demonstrating that digital economy enhances GIE. By integrating the digital economy with the quality and efficiency of green innovation into a unified analytical framework, our study confirms the "green attributes" of the digital economy [90]. The capacity of digital economy to augment resource integration and environmental monitoring has emerged as a crucial mechanism for achieving GIQ [2]. Furthermore, the standardization, generalization, and modularization of digital technologies enable their cost-effective dissemination and application across various sectors, significantly boosting GIE [1].

Concerning the control variables, URB exhibits contrasting impacts on the quality and efficiency of green innovation. Notably, urbanization significantly enhances GIQ but exerts a notable negative influence on GIE. This phenomenon may stem from the dual nature of urbanization: on one hand, the concentration of innovative resources and the knowledge spillover effects associated with urban settings foster a rich environment for green innovation, enhancing its quality; on the other hand, such agglomeration is also linked to challenges like excessive resource consumption and environmental degradation, which impede the enhancement of GIE [91]. The influence of financial development (FIN) on green innovation is negative, indicating that the prevailing financial model in China does not support improvements in GIQ and GIE. This finding agrees with that reported by Liu et al. (2022) [92]. Variables such as MAR, OPEN, and INF positively impact the quality and efficiency of green innovation. Marketization potentially enhances resource allocation efficiency, thereby lowering the marginal costs of green technological innovation and consequently benefiting its quality and efficiency [80,93]. Openness to international markets facilitates the cross-border flow of technology and talent, thus revitalizing green innovation efforts [94]. Furthermore, advancements in infrastructure provide robust support for the research, development, production, and marketing of green innovations, thereby promoting improvements in GIQ and GIE [95]. Nonetheless, the analyses reveal that, despite their positive effects, the impacts of MAR, OPEN, and INF on green innovation are not statistically significant. This suggests that the potential of these factors to foster green innovation in the Chinese context remains largely unknown.

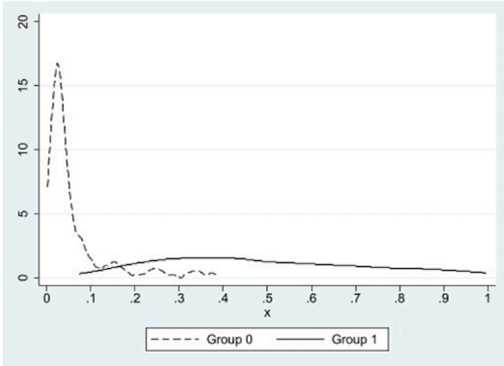
Table 1
Descriptive statistics.

Variable	N	Mean	SD	Min	Max
GIE	480	0.356	0.267	0.016	1.371
GIQ	480	0.538	1.093	0.002	10.982
DE	480	0.167	0.096	0.016	0.672
URB	480	54.407	13.977	26.870	89.600
MAR	480	6.478	2.141	−1.420	11.710
FIN	480	2.984	1.155	1.390	8.130
OPEN	480	0.313	0.347	0.011	1.649
INF	480	0.829	0.492	0.039	2.118

Note: Original data in table from: https://data.cnki.net/.



a. Kernel density distribution of GIE



b. Kernel density distribution of GIQ

Fig. 2. Kernel density distribution of the efficiency and quality of green innovation.

Table 2
Baseline regression results of the digital economy on the quality and efficiency of green innovation.

	GIQ	GIE	GIQ	GIE
	(1)	(2)	(3)	(4)
DE	11.503[b]	2.741[c]	1.470[b]	2.487[c]
	(2.400)	(6.690)	(2.430)	(5.070)
URB			0.0476[c]	−0.009[a]
			(3.150)	(-1.800)
MAR			0.0435	0.029
			(1.230)	(1.640)
FIN			−0.112	−0.091[c]
			(-1.470)	(-4.010)
OPEN			0.227	0.022
			(0.870)	(0.180)
INF			0.149	0.127
			(0.670)	(1.470)
CONS	−1.377[a]	−0.100	3.488[c]	0.410
	(-1.730)	(-1.47)	(3.52)	(1.290)
IND	Yes	Yes	Yes	Yes
YEAR	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.762	0.784	0.980	0.777
F	5.760	44.787	4.463	12.236

Note: *t* statistics are in parentheses.
[a] $p < 0.1$.
[b] $p < 0.05$.
[c] $p < 0.01$.

4.2. Endogeneity test

To address the potential endogeneity of the effect of digital economy on GIQ and GIE, we employed an instrumental variables approach. Drawing on the works of Zhang et al. (2022) [96] and Lu et al. (2023) [97], we created an instrumental variable. This variable is an interaction term between the total volume of postal and telecommunications businesses in 1984 and the average value of China's digital economy development index with a time lag, excluding the province under study. This type of instrumental variable is known as "Shift-Share," as outlined by Goldsmith-Pinkham et al. (2020) [98]. The rationale for this choice is twofold. First, the historical volume of the postal and telecommunications businesses is pertinent because it reflects the pre-existing level of telecommunications infrastructure and demand in the region, thus influencing digital economy development. Second, the influence of historical business volume on current green innovation diminishes over time, satisfying the exogeneity condition.

Table 3 presents the results of the regression analysis using the instrumental variables technique. Prior to executing such analyses, we conducted the Wu-Hausman test to evaluate the endogeneity concerns of the explanatory variables in our model [99]. The test outcomes indicated the presence of endogeneity within the digital economy variables, suggesting that our model's estimations might be compromised by inherent internal correlations, thereby affecting the estimations' consistency and validity. Consequently, the employment of the instrumental variables method is deemed essential for enhancing the robustness of our estimation outcomes. In Table 3, the regression findings from the first stage are illustrated in Columns (1) and (3), affirming the pertinence of our chosen

Table 3
Endogeneity test results of digital economy and green innovation.

	GIQ		GIE	
	The first stage	The second stage	The first stage	The second stage
	(1)	(2)	(3)	(4)
DE		11.774* (2.010)		3.520*** (4.820)
IV	0.601*** (7.410)		0.601*** (7.410)	
Controls	Yes	Yes	Yes	Yes
IND	Yes	Yes	Yes	Yes
YEAR	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2		0.420		0.284
Cragg-Donald Wald F		634.637		634.637
Kleibergen-Paap rk LM		11.346		11.346
Kleibergen-Paap rk Wald F		54.909		54.909
Wu- Hausman Test		24.02***		19.54***

instrumental variables. Furthermore, the Kleibergen-Paap rk Wald F-statistic value is 54.909, markedly surpassing the 10 % critical value threshold for weak instrumental variables, thus substantiating the rationality and effectiveness of the selected instrumental variables. The regression outcomes of the second stage, detailed in Columns (2) and (4), demonstrate that even after addressing endogeneity concerns, the positive influence of digital economy on GIQ and GIE remains significant and aligns with our benchmark regression findings. These results bolster the credibility of our conclusion that digital economy significantly enhances GIQ and GIE.

4.3. Robustness tests

We conducted a suite of robustness tests to bolster the credibility of the benchmark regression. First, we acknowledged that this study utilized an instrumental variable approach to address endogeneity. To mitigate any potential reciprocal causality between digital economy and green innovation, we run the regression with the main variables lagged by one period. These results appear in Columns (1) and (2) present Table 4. Next, to minimize the bias stemming from the indicator evaluation methods, we reassessed the digital economy using principal component analysis and re-ran the regression. Columns (3) and (4) of Table 4 present the findings. Lastly, we note that China's digital economy has experienced a significantly higher average annual growth rate than its GDP since 2012. To account for this, we adjusted the regression timeframe to include samples from 2012 to 2019. Columns (5) and (6) display the 4. Across all the robustness tests, the positive impact of digital economy on GIQ and GIE remained significant. This reaffirms the role of digital economy in "enhancing the quality and improving the efficiency" of green innovation. Hence, Hypothesis 1 is supported.

5. Further analysis: the impact of fiscal decentralization

5.1. Digital economy, fiscal decentralization, and green innovation

Based on the previous empirical tests, the results show that digital economy has a significant "quality enhancement and efficiency improvement" effect in promoting regional green innovation. Furthermore, this section focuses on the impact of the fiscal decentralization on this process. As outlined in earlier theoretical analyses, green innovation requires nuanced governmental oversight due to its "double externality" features [18]. While the central government issues comprehensive green innovation guidelines through various policies, on-the-ground implementation largely falls under local governments [100]. In China's institutional environment, an

Table 4
Robustness test results of digital economy and green innovation.

	GIQ	GIE	GIQ	GIE	GIQ	GIE
	(1)	(2)	(3)	(4)	(5)	(6)
	Main variables lagged by one period		Replacement of explanatory variable measures		Changing the regression years	
DE/L.DE	8.283* (4.183)	2.432*** (4.800)	1.470** (2.430)	1.298** (2.220)	5.166* (1.980)	1.397*** (2.870)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
CONS	6.835 (4.028)	0.460 (0.192)	3.488*** (3.520)	0.160 (0.420)	8.488* (1.790)	1.283*** (2.990)
IND	Yes	Yes	Yes	Yes	Yes	Yes
YEAR	Yes	Yes	Yes	Yes	Yes	Yes
N	450	450	480	480	240	240
R^2	0.842	0.804	0.980	0.705	0.932	0.871
F	5.439	12.014	4.463	4.343	2.693	9.909

elevated degree of fiscal decentralization allows for expanded policy autonomy at the local government level [19].

Therefore, we introduced an interaction term between digital economy and fiscal decentralization into our model. The results presented in Table 5 provide compelling evidence. In Columns (2) and (4), the interaction term (DE*FD) demonstrates a positive correlation at the 5 % significance level, underlining the existence of notable synergies between digital economy and fiscal decentralization. When viewed alongside the main effect, these results suggest that the digital economy exerts a more potent "quality enhancement and efficiency improvement" influence on green innovation in regions with higher levels of fiscal decentralization. These findings suggest that, within the existing fiscal decentralization framework, local governments are more inclined to adopt a "race to the top" approach. This approach involves formulating "green" policies that align with the local industry structure and development level. It aims to guide digital economy towards a direction that is green, ecologically friendly, and innovative. Consequently, this enhances the positive impact of digital economy on green innovation. Thus, Hypothesis 2a was confirmed. Our findings support those of Lo (2015) [101]and Yi et al. (2023) [102]. They argue that fiscal decentralization is a prerequisite for promoting environmental improvements.

5.2. Heterogeneity analysis based on different perspectives

Performance appraisal mechanisms shape local government behavior within an fiscal decentralization framework [103]. While our prior analysis suggests that Chinese local governments under the existing fiscal system generally lean towards a "race to the top" to boost green innovation, this tendency may not be constant.

Based on the theoretical analysis presented in the previous section, environmental performance assessments and economic development levels can affect this strategic choice [77]. To this end, we introduced two variables, environmental performance and economic development, to examine the relationship between fiscal decentralization and the impact of digital economy on green innovation from both vertical and horizontal perspectives.

1 Vertical Analysis: Assessment of Environmental Performance

According to China's *Eleventh Five-Year Plan for environmental protection*, released in 2007, added binding environmental indicators to local government performance appraisals. To examine the evolution of this appraisal system, we adopted the research methodology of Yan et al. (2021) [104]. We partitioned our sample using 2007 as the breakpoint. The regression results are presented in Table 6, with columns (1) and (2) displaying the estimates for GIQ, and columns (3) and (4) for GIE.

It can be observed that the interaction term between the digital economy and fiscal decentralization exhibits a significant positive effect on GIQ, both before and after the watershed year of 2007. Notably, the coefficient of the DE*FD interaction term increased to 5.725 in the post-2007 period, more than doubling its pre-2007 value and passing the Chow test for structural breaks. This finding suggests that since 2007, when environmental performance was incorporated into local government appraisals, municipal authorities in China have increased their emphasis on green development under the dual incentives of economic and ecological criteria. fiscal decentralization further amplifies the positive impact of digital economy on fostering GIQ. Our results provide new empirical evidence to support the "Weak Porter Hypothesis" [105]: when the central government prioritizes green development, local governments in China face incentives to strengthen environmental governance, which in turn stimulates the generation of green innovation.

For GIE, although the coefficient of the DE*FD interaction term became positive after 2007, it failed to reach statistical significance. This implies that while China has placed increased emphasis on environmental performance assessment since 2007 and has continued to augment investments in environmental governance, GIE has not exhibited commensurate improvement. There are two possible explanations for this observation. First, it may be difficult to instantaneously enhance GIE through elevated short-term financial investments [106]. Second, some regions may engage in symbolic compliance with assessments, prioritizing the quantity of innovation outputs over their efficiency, thus impeding improvements in innovation efficiency [107]. Hypothesis 2b was partially supported.

Table 5
Analysis of fiscal decentralization synergies.

	GIQ		GIE	
	(1)	(2)	(3)	(4)
DE	7.717*	−3.804	2.484***	1.645***
	(1.930)	(-1.030)	(5.190)	(3.680)
FD	0.057	−0.598***	−0.005	−0.052
	(0.490)	(-3.100)	(-0.070)	(-0.790)
DE*FD		5.498**		0.400***
		(2.610)		(2.930)
Controls	Yes	Yes	Yes	Yes
CONS	6.531	1.212	0.413	0.026
	(0.105)	(1.450)	(1.350)	(0.090)
IND	Yes	Yes	Yes	Yes
YEAR	Yes	Yes	Yes	Yes
N	480	480	480	480
R^2	0.830	0.906	0.800	0.807
F	8.663	9.190	11.743	13.416

Table 6
Analysis of heterogeneity in environmental performance appraisal.

	GIQ		GIE	
	(1)	(2)	(3)	(4)
	Year<2007	Year ≥ 2007	Year<2007	Year ≥ 2007
DE	−3.868**	−4.502	2.944	1.585***
	(-2.210)	(-1.120)	(0.850)	(3.150)
FD	−0.092***	−1.002***	−0.247	0.00344
	(-3.780)	(-2.830)	(-1.060)	(0.040)
DE*FD	2.500***	5.725**	−0.0475	0.301
	(4.060)	(2.420)	(-0.060)	(1.540)
Controls	Yes	Yes	Yes	Yes
CONS	0.717**	2.085*	−1.605	0.235
	(2.460)	(1.780)	(-0.670)	(0.560)
IND	Yes	Yes	Yes	Yes
YEAR	Yes	Yes	Yes	Yes
N	90	390	90	390
R^2	0.992	0.917	0.757	0.833
F	10.718	7.681	1.010	9.858

Table 7
Analysis of heterogeneity in levels of economic development.

	GIQ		GIE	
	(1)	(2)	(3)	(4)
	Low economic development group	High economic development group	Low economic development group	High economic development group
DE	2.219**	−5.797	0.0685	2.750***
	(2.300)	(-1.040)	(0.070)	(5.150)
FD	0.0282	−0.790***	−0.360	−0.042
	(0.13)	(-3.17)	(-1.08)	(-0.940)
DE*FD	0.563	5.800**	1.221	0.227*
	(0.650)	(2.450)	(0.890)	(1.740)
Controls	Yes	Yes	Yes	Yes
CONS	0.0149	2.117	−0.358	0.670*
	(0.030)	(1.720)	(-0.550)	(1.960)
IND	Yes	Yes	Yes	Yes
YEAR	Yes	Yes	Yes	Yes
N	240	240	240	240
R^2	0.735	0.915	0.658	0.848
F	8.295	5.020	1.314	17.941

2 Horizontal Comparison: Economic Development

Building on our earlier analysis, we recognize that economic development influences local government choices in green strategy and the material foundation for technological innovation. To this end, we categorized the samples based on the median annual per capita GDP, dividing them into high and low economic development groups. Table 7tbl7 displays the results, where columns (1) and (2) show the results for GIQ and columns (3) and (4) show the results for GIE.

For both GIQ and GIE, the interaction effects of digital economy and fiscal decentralization on green innovation exhibited a more pronounced positive impact in regions with higher levels of economic development. This finding suggests that digital economy is more effective at catalyzing green innovation in economically advanced regions, thereby lending empirical support to Hypothesis 2c. Fiscal decentralization appears to be more conducive to harnessing the potential of digital economy to stimulate green innovation in regions with higher economic development.

Specifically, in more economically developed regions, local governments not only possess abundant human, material, and financial resources to undertake environmental governance and green technology investment initiatives, but are also more likely to formulate favorable policies that incentivize enterprises and individuals to participate in green innovation activities [108,109]. These local authorities are better positioned to leverage the autonomy afforded by the fiscal decentralization to foster the in-depth development of the digital economy and its promotion of environmentally friendly innovation, while accounting for local economic characteristics and development needs. Conversely, in regions with relatively underdeveloped economies, local governments may be more inclined to prioritize economic growth objectives due to resource scarcity, relegating environmental governance and green innovation to lower priority [108]. In such regions, fiscal decentralization may not provide sufficient incentives for digital economy to stimulate green innovation.

5.3. Evidence from spatial effects

According to Tobler's First Law of Geography, the closer the distance, the greater the impact [60]. Especially for digital economy, which can overcome spatial limitations, its impact is not limited to local areas [96]. Therefore, we introduce spatial measurements for the analysis. Before examining the spatial regression, we first established its validity through a series of tests. We first tested the spatial autocorrelation of GIQ and GIE by applying Moran's I index to the adjacency matrix W_ij^A (see Appendix A). The test results revealed significant spatial autocorrelation for GIQ and GIE across most observed years, justifying the use of spatial econometric models [110].

For model selection, we undertake a variety of statistical tests, including the LM, Hausman, LR, and Wald tests (see Appendix B). The collective outcomes indicate that the Spatial Durbin Model (SDM) is not reducible to either the Spatial Autocorrelation Model (SAR) or the Spatial Error Model (SEM) [110]. This finding affirms that the fixed-effects SDM is the optimal model choice.

Table 8 presents the estimation results for the two-way fixed effects of SDM. Columns (1)–(2) show the results of the adjacency matrix, and columns (3)–(4) show the results of the distance matrix. Notably, the spatial dependence parameter (rho coefficient) was statistically significant, reinforcing the appropriateness of our spatial model. The interaction term between digital economy and fiscal decentralization maintained its significance for the local green innovation. When considering the main effect results without the interaction term (see Appendix C), it was evident that fiscal decentralization and digital economy continued to exert a synergistic influence on local green innovation, even when accounting for spatial factors. Hypothesis 2d is verified.

The SDM includes spatial lag terms for both dependent and independent variables, which can introduce bias into the results [60]. To address this, we employed partial differentiation to further decompose the results. Table 9 presents the direct, indirect, and total effects of the variables using this method. Our findings indicated that the direct effects of the interaction term between digital economy and fiscal decentralization (DE × FD) on GIQ improvement were positive and significant at the 1 % level. This analysis corroborates the notion that fiscal decentralization can further catalyze the positive influence of digital economy on the quality and efficiency of green innovation. Notably, the coefficients of the interaction term between fiscal decentralization and digital economy are consistently positive and statistically significant across the spatial weight matrices. This finding supports the assertion that the interplay between digital economy and fiscal decentralization generates positive spatial spillover effects. In the realm of green innovation, local governments in China exhibit a predilection for pursuing a "race to the top" strategy, which entails increasing financial subsidies and tightening environmental regulations to compel firms to undertake green technological innovations, thereby enhancing their innovation performance [111]. Such a strategy exerts a "demonstration diffusion" effect [112], prompting neighboring regions to strengthen their environmental regulations as well, thus fostering the emergence of green innovations across contiguous areas. These observations were consistent with those of Song et al. (2018) [113].

6. Conclusions and policy implications

6.1. Conclusions

Our study systematically explores the impact of digital economy and fiscal decentralization on the quality and efficiency of green innovation. By analyzing panel data from 30 provinces in China from 2004 to 2019, we employed a two-way fixed-effects model, instrumental variable techniques, and spatial econometric models. This study reveals the dual promotional role of digital economy in enhancing green innovation, which was substantiated through multiple robustness checks and endogeneity tests. Further analysis

Table 8
Results of spatial regression.

	GIQ	GIE	GIQ	GIE
	(1)	(2)	(3)	(4)
	Adjacency matrix W_ij^A		Distance matrix W_ij^D	
DE	−1.925**	1.575***	−3.396***	1.501***
	(-2.300)	(4.990)	(-3.930)	(4.700)
FD	−0.556***	−0.023	−0.604***	−0.067*
	(-5.810)	(-0.630)	(-6.320)	(-1.910)
DE*FD	4.929***	0.281***	5.437***	0.380***
	(17.690)	(2.680)	(19.930)	(3.760)
W*DE	−2.085	−2.616***	−4.939	−4.023***
	(-1.390)	(-4.840)	(-1.440)	(-3.170)
W*FD	0.288	−0.052	−0.324	−0.213
	(1.480)	(-0.720)	(-0.930)	(-1.640)
W*DE*FD	−1.770**	0.289	−0.403	0.769
	(-2.520)	(1.240)	(-0.280)	(1.490)
CONS	YES	YES	YES	YES
Rho	0.501***	0.301***	0.601***	0.462***
	(10.070)	(5.600)	(9.160)	(5.770)
sigma2_e	0.101***	0.014***	0.103***	0.014***
	(15.060)	(15.360)	(15.370)	(15.420)
N	480	480	480	480
R^2	0.716	0.443	0.697	0.450

Table 9
Spatial effects decomposition results.

		GIQ	GIE	GIQ	GIE
		(1)	(2)	(3)	4)
		Adjacency matrix W_{ij}^{A}		Distance matrix W_{ij}^{D}	
Direct Effect	DE	−2.354**	1.418***	−3.803***	1.387***
		(-2.560)	(4.330)	(-4.060)	(4.140)
	FD	−0.554***	−0.028	−0.649***	−0.078**
		(-5.760)	(-0.810)	(-6.690)	(-2.240)
	DE*FD	5.049***	0.316***	5.636***	0.422***
		(16.140)	(2.930)	(18.120)	(3.930)
Indirect Effect	DE	−5.450**	−2.844***	−16.860**	−5.943***
		(-2.050)	(-3.990)	(-1.980)	(-2.610)
	FD	0.046	−0.072	−1.655*	−0.430*
		(0.140)	(-0.790)	(-1.890)	(-1.830)
	DE*FD	1.229	0.484	6.985*	1.680*
		(1.030)	(1.530)	(1.920)	(1.750)
Total Effect	DE	−7.804**	−1.426*	−20.662**	−4.556*
		(-2.500)	(-1.740)	(-2.330)	(-1.920)
	FD	−0.508	−0.100	−2.304**	−0.507**
		(-1.350)	(-1.000)	(-2.520)	(-2.080)
	DE*FD	6.278***	0.800**	12.621***	2.101**
		(4.540)	(2.210)	(3.310)	(2.080)

revealed a significant synergistic effect between digital economy and fiscal decentralization. Local governments tend to adopt a “race to the top” strategy, which amplifies the impact of digital economy on promoting green innovation. Heterogeneity analysis indicated that the influence of fiscal decentralization on the relationship between digital economy and green innovation varied with the environmental performance indices and levels of economic development. Specifically, the synergistic effects are more pronounced in economically advanced areas when environmental performance assessments are emphasized. From a spatial perspective, fiscal decentralization is more likely to produce a “demonstration effect” rather than a “pollution haven” in neighboring regions, thereby fostering the role of the digital economy in advancing green innovation in these areas.

This study used data from China to explore the role of the digital economy in green innovation from the dual perspectives of quality and efficiency, thereby addressing a gap in the literature. Based on data from China, the conclusions can be applied to other countries and provide empirical support for digital economys role in driving green innovation. The existing literature has extensively discussed the link between digital economy and green innovation [7,72]; however, the role of governmental functions has been largely overlooked. Fiscal decentralization is critical; however, the impact of Chinese-style fiscal decentralization on green innovation remains controversial. Therefore, we incorporate Chinese-style fiscal decentralization as a moderating variable to elucidate its significance in enhancing digital economy contribution to green innovation, offering new empirical evidence for the Porter Hypothesis [114]. Our findings confirm that fiscal decentralization is conducive to environmental protection [115,116] and expand our understanding of its impact from the perspectives of environmental performance and economic development. Moreover, we validate the “demonstration effect” of fiscal decentralization from a spatial perspective; that is, fiscal decentralization can enhance the positive impact of digital economy on green innovation in neighboring regions. These findings are instructive not only for China but also for other nations, particularly those with similar fiscal systems, governmental functions, and levels of digital economic development. The development of digital economy promotes the effective allocation of information and resources, which can enhance green innovation and improve resource-use efficiency, potentially transcending specific national economic systems. Furthermore, appropriate devolution of fiscal powers facilitates local governments in better harnessing the green “effect.”

6.2. Policy recommendations

Based on our findings, we offer the following policy insights that are not only applicable to China, but may also be extendable to other countries:

First, policy-makers must acknowledge the pivotal role of digital economy in fostering green innovation. A multifaceted approach is imperative to actively promote the advancement of digital economy. Integrating digital economy with emerging sectors such as clean technology and pollution control is crucial, as it facilitates the digital transformation of traditional industries. These measures curb transaction costs and enable efficient green innovation.

Second, given the synergistic effects of fiscal decentralization and digital economy in catalyzing green innovation, it is imperative for governments, particularly those in centralized nations, to further reinforce fiscal decentralization efforts. Augmentation of fiscal autonomy according to the needs of local governments is warranted. Furthermore, considering the influence of performance evaluation criteria and economic development levels on governmental behavior, urgent reforms of the performance appraisal system are necessary. Such reforms should give greater weight to green development indicators and delineate local government responsibilities with enhanced clarity. For financially constrained, less developed regions, increasing environmental protection transfer has become necessary. Concurrently, robust information disclosure and oversight mechanisms must be instituted to ensure judicious utilization of funds.

Finally, to harness the spatial spillover effects engendered by fiscal decentralization and digital economy, emphasis must be placed on fortifying synergies and cooperation among local governments. Local governments should be dissuaded from free-riding behavior in green innovation, and the formation of a benign inter-regional competition dynamic should be encouraged. To this end, local governments should be guided to cultivate unique competitive advantages in environmental protection by leveraging their distinctive endowments. However, concerted efforts are required to establish regionally integrated, open, and coordinated economic systems and dismantle interregional barriers that impede factor mobility. This approach would facilitate the efficient flow and sharing of green innovation factors among neighboring regions, promoting a continuous positive spatial spillover effect, and ultimately fostering a synergistic elevation of regional green innovation across locales.

6.3. Limitations and future research

While this study provides a comprehensive analysis of the interplay among digital economy, fiscal decentralization, and green innovation, several limitations warrant acknowledgment. First, the study period was limited to 2004–2019 to avoid distortions from the COVID-19 pandemic, which ensures data integrity but limits the analysis of recent trends. Future research should include data beyond 2019. Additionally, the analysis relied on regional-level data, constraining its granularity. Future research should use more granular city-level data for nuanced insights. Second, the measures employed to assess digital economy could benefit from further refinement to capture the multifaceted complexities more holistically. Third, the study does not sufficiently account for certain uncertainties, such as policy volatility and local protectionism, which could potentially influence digital economy, fiscal decentralization, and both the quality and efficiency of green innovation. These limitations not only delineate avenues for future scholarly inquiry, but also contextualize the bounds of the study's current contributions.

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Data availability statement

Has data associated with your study been deposited into a publicly available repository? No.
Data will be made available on request.

CRediT authorship contribution statement

Zijun Liu: Writing – review & editing, Writing – original draft. **Bingjie Liu:** Writing – original draft, Data curation, Conceptualization. **Hang Luo:** Methodology, Formal analysis, Data curation. **Sheng Chen:** Funding acquisition.

Declaration of competing interest

The authors have no relevant financial or non-financial interests to disclose.
We declare that this manuscript has not been published previously and it is not under consideration for publication elsewhere at the time of submission.

Appendix A

Table A.1
Moran's index table

YEAR	GIQ		GIE	
	I	*P*-value	I	*P*-value
2004	0.216	0.003	0.036	0.231
2005	0.211	0.003	0.121	0.097
2006	0.230	0.003	0.170	0.013
2007	0.198	0.005	0.272	0.005
2008	0.120	0.028	0.292	0.004
2009	0.170	0.010	0.010	0.338
2010	0.172	0.009	0.163	0.046
2011	0.195	0.004	0.239	0.011
2012	0.230	0.002	0.486	0.000
2013	0.231	0.001	0.477	0.000
2014	0.198	0.001	0.465	0.000
2015	0.254	0.000	0.277	0.005

(*continued on next page*)

Table A.1 (*continued*)

YEAR	GIQ		GIE	
	I	*P*-value	I	*P*-value
2016	0.304	0.000	0.360	0.001
2017	0.224	0.002	0.268	0.008
2018	0.198	0.004	0.380	0.000
2019	0.169	0.007	0.387	0.000

Appendix B

Table B.1
Spatial model testing

Variable	GIQ		GIE	
	Statistics	P-value	Statistics	P-value
LM_{lag}	75.778	0.000	28.534	0.000
LM_{err}	35.883	0.000	10.436	0.001
Robust LM_{lag}	40.923	0.000	19.455	0.000
Robust LM_{err}	1.027	0.311	1.356	0.244
LR_{lag}	77.14	0.000	60.10	0.000
LR_{err}	55.60	0.000	38.42	0.000
$Wald_{lag}$	77.22	0.000	51.95	0.000
$Wald_{err}$	50.70	0.000	38.94	0.000
Hausman	35.54	0.000	32.51	0.000

Appendix C

Table C.1
Spatial main effects of the digital economy

	GIQ	GIE	GIQ	GIE
	(1)	(2)	(3)	(4)
	Adjacency matrix W_{ij}^{A}		Distance matrix W_{ij}^{D}	
DE	7.431***	2.087***	7.642***	2.259***
	(8.820)	(8.450)	(8.490)	(9.120)
FD	0.086	0.015	0.032	−0.020
	(0.750)	(0.430)	(0.260)	(-0.600)
W*DE	−6.373***	−2.149***	−8.487***	−2.631***
	(-5.730)	(-6.690)	(-3.470)	(-3.970)
W*FD	−0.058	−0.010	−0.337	−0.078
	(-0.280)	(-0.160)	(-0.970)	(-0.820)
CONS	YES	YES	YES	YES
Rho	0.435***	0.319***	0.469***	0.488***
	(8.540)	(6.090)	(5.870)	(6.400)
sigma2_e	0.171***	0.015***	0.190***	0.014***
	(15.190)	(15.340)	(15.420)	(15.420)
N	480	480	480	480
R^2	0.053	0.201	0.112	0.135

References

[1] Z. Zhiyong, X. Yongbin, C. Jiaying, Digital economy, industrial structure upgrading and green innovation efficiency of family enterprises, Int. Enterpren. Manag. J. (2023), https://doi.org/10.1007/s11365-023-00854-5.

[2] Y. Liu, Y. Xie, K. Zhong, Impact of digital economy on urban sustainable development: evidence from Chinese cities, Sustain. Dev. (2023) sd.2656, https://doi.org/10.1002/sd.2656.

[3] M. Wang, X. Li, S. Wang, Discovering research trends and opportunities of green finance and energy policy: a data-driven scientometric analysis, Energy Pol. 154 (2021) 112295, https://doi.org/10.1016/j.enpol.2021.112295.

[4] X. Liu, C. Wang, H. Wu, C. Yang, K. Albitar, The impact of the new energy demonstration city construction on energy consumption intensity: exploring the sustainable potential of China's firms, Energy 283 (2023) 128716, https://doi.org/10.1016/j.energy.2023.128716.

[5] W. Zhang, Q. Luo, Y. Zhang, A. Yu, Does green credit policy matter for corporate exploratory innovation? Evidence from Chinese enterprises, Econ, Anal. Polit. 80 (2023) 820–834, https://doi.org/10.1016/j.eap.2023.09.024.

[6] W. Zhang, H. Fan, Q. Zhao, Seeing green: how does digital infrastructure affect carbon emission intensity? Energy Econ. 127 (2023) 107085 https://doi.org/10.1016/j.eneco.2023.107085.

[7] S. Luo, N. Yimamu, Y. Li, H. Wu, M. Irfan, Y. Hao, Digitalization and sustainable development: how could digital economy development improve green innovation in China? Bus. Strat. Environ. 32 (2023) 1847–1871, https://doi.org/10.1002/bse.3223.

[8] L. Wang, Y. Chen, T.S. Ramsey, G.J.D. Hewings, Will researching digital technology really empower green development? Technol. Soc. 66 (2021) 101638 https://doi.org/10.1016/j.techsoc.2021.101638.

[9] H. Tian, Y. Li, Y. Zhang, Digital and intelligent empowerment: can big data capability drive green process innovation of manufacturing enterprises? J. Clean. Prod. 377 (2022) 134261 https://doi.org/10.1016/j.jclepro.2022.134261.

[10] S. Cao, L. Nie, H. Sun, W. Sun, F. Taghizadeh-Hesary, Digital finance, green technological innovation and energy-environmental performance: evidence from China's regional economies, J. Clean. Prod. 327 (2021) 129458, https://doi.org/10.1016/j.jclepro.2021.129458.

[11] Q. Dou, X. Gao, The double-edged role of the digital economy in firm green innovation: micro-evidence from Chinese manufacturing industry, Environ. Sci. Pollut. Res. 29 (2022) 67856–67874, https://doi.org/10.1007/s11356-022-20435-3.

[12] Wanting Bai, Jian Hou, Jiajun Xu, Jiancheng Chen, Does digital economy development successfully drive the quality of green innovation in China? Pol. J. Environ. Stud. 32 (2023) 2001–2014, https://doi.org/10.15244/pjoes/159316.

[13] X. Xiang, C. Liu, M. Yang, Who is financing corporate green innovation? Int. Rev. Econ. Finance 78 (2022) 321–337, https://doi.org/10.1016/j.iref.2021.12.011.

[14] G. Hu, X. Wang, Y. Wang, Can the green credit policy stimulate green innovation in heavily polluting enterprises? Evidence from a quasi-natural experiment in China, Energy Econ. 98 (2021) 105134, https://doi.org/10.1016/j.eneco.2021.105134.

[15] X. Zhan, R.Y.M. Li, X. Liu, F. He, M. Wang, Y. Qin, J. Xia, W. Liao, Fiscal decentralisation and green total factor productivity in China: SBM-GML and IV model approaches, Front. Environ. Sci. 10 (2022), https://doi.org/10.3389/fenvs.2022.989194.

[16] M. Elheddad, N. Djellouli, A.K. Tiwari, S. Hammoudeh, The relationship between energy consumption and fiscal decentralization and the importance of urbanization: evidence from Chinese provinces, J. Environ. Manag. 264 (2020) 110474, https://doi.org/10.1016/j.jenvman.2020.110474.

[17] Y. Sun, A. Razzaq, Composite fiscal decentralisation and green innovation: imperative strategy for institutional reforms and sustainable development in OECD countries, Sustain. Dev. 30 (2022) 944–957, https://doi.org/10.1002/sd.2292.

[18] G. Hu, X. Wang, Y. Wang, Can the green credit policy stimulate green innovation in heavily polluting enterprises? Evidence from a quasi-natural experiment in China, Energy Econ. 98 (2021) 105134, https://doi.org/10.1016/j.eneco.2021.105134.

[19] X. Pu, M. Zeng, W. Zhang, Does fiscal decentralization really matter for public service satisfaction? Appl. Econ. 0 (2023) 1–19, https://doi.org/10.1080/00036846.2023.2267815.

[20] S. Shan, M. Ahmad, Z. Tan, T.S. Adebayo, R.Y. Man Li, D. Kirikkaleli, The role of energy prices and non-linear fiscal decentralization in limiting carbon emissions: tracking environmental sustainability, Energy 234 (2021) 121243, https://doi.org/10.1016/j.energy.2021.121243.

[21] J. Xia, X. Zhan, R.Y.M. Li, L. Song, The relationship between fiscal decentralization and China's low carbon environmental governance performance: the malmquist index, an SBM-DEA and systematic GMM approaches, Front. Environ. Sci. 10 (2022), https://doi.org/10.3389/fenvs.2022.945922.

[22] C. Zhao, F. Feng, Y. Chen, X. Li, Local government competition and regional innovation efficiency: from the perspective of China-style fiscal federalism, Sci. Publ. Pol. 48 (2021) 488–489, https://doi.org/10.1093/scipol/scab023.

[23] X. Lü, P.F. Landry, Show me the money: interjurisdiction political competition and fiscal extraction in China, Am. Polit. Sci. Rev. 108 (2014) 706–722, https://doi.org/10.1017/S0003055414000252.

[24] F. Wang, T. Rani, A. Razzaq, Environmental impact of fiscal decentralization, green technology innovation and institution's efficiency in developed countries using advance panel modelling, Energ Environ-Uk 34 (2023) 1006–1030, https://doi.org/10.1177/0958305X221074727.

[25] Y. Li, F. Wang, The corporate path to green innovation: does the digital economy matter? Environ. Sci. Pollut. Res. (2023) https://doi.org/10.1007/s11356-023-27818-0.

[26] M. Chi, S. Muhammad, Z. Khan, S. Ali, R.Y.M. Li, Is centralization killing innovation? The success story of technological innovation in fiscally decentralized countries, Technol. Forecast. Soc. 168 (2021) 120731, https://doi.org/10.1016/j.techfore.2021.120731.

[27] Y. Qiu, W. Liu, J. Wu, Digital economy and urban green innovation: from the perspective of environmental regulation, J. Environ. Plann. Manag. (2023) 1–23, https://doi.org/10.1080/09640568.2023.2244668, 0.

[28] G. Li, X. Li, L. Huo, Digital economy, spatial spillover and industrial green innovation efficiency: empirical evidence from China, Heliyon 9 (2023) e12875, https://doi.org/10.1016/j.heliyon.2023.e12875.

[29] R. Lin, Z. Xie, Y. Hao, J. Wang, Improving high-tech enterprise innovation in big data environment: a combinative view of internal and external governance, Int. J. Inf. Manag. 50 (2020) 575–585, https://doi.org/10.1016/j.ijinfomgt.2018.11.009.

[30] G. Yang, Y. Nie, H. Li, H. Wang, Digital transformation and low-carbon technology innovation in manufacturing firms: the mediating role of dynamic capabilities, Int. J. Prod. Econ. 263 (2023) 108969, https://doi.org/10.1016/j.ijpe.2023.108969.

[31] X. Yang, H. Wu, S. Ren, Q. Ran, J. Zhang, Does the development of the internet contribute to air pollution control in China? Mechanism discussion and empirical test, Struct. Change Econ. Dynam. 56 (2021) 207–224, https://doi.org/10.1016/j.strueco.2020.12.001.

[32] Z. Lv, X. Li, W. Wang, B. Zhang, J. Hu, S. Feng, Government affairs service platform for smart city, Future Generat. Comput. Syst. 81 (2018) 443–451, https://doi.org/10.1016/j.future.2017.08.047.

[33] G. Lian, A. Xu, Y. Zhu, Substantive green innovation or symbolic green innovation? The impact of ER on enterprise green innovation based on the dual moderating effects, Journal of Innovation & Knowledge 7 (2022) 100203, https://doi.org/10.1016/j.jik.2022.100203.

[34] D. Dougherty, D.D. Dunne, Digital science and knowledge boundaries in complex innovation, Organ. Sci. 23 (2012) 1467–1484, https://doi.org/10.1287/orsc.1110.0700.

[35] J. Zhao, L. Yu, X. Xi, S. Li, Knowledge percolation threshold and optimization strategies of the combinatorial network for complex innovation in the digital economy, Omega 120 (2023) 102913, https://doi.org/10.1016/j.omega.2023.102913.

[36] P. Mikalef, I.O. Pappas, J. Krogstie, M. Giannakos, Big data analytics capabilities: a systematic literature review and research agenda, Inf Syst E-Bus Manage 16 (2018) 547–578, https://doi.org/10.1007/s10257-017-0362-y.

[37] K.-L. Wang, T.-T. Sun, R.-Y. Xu, Z. Miao, Y.-H. Cheng, How does internet development promote urban green innovation efficiency? Evidence from China, Technol. Forecast. Soc. Change 184 (2022) 122017, https://doi.org/10.1016/j.techfore.2022.122017.

[38] A. Anagnostopoulos, M.E. Navarro, M. Stefanidou, P. Seferlis, G. Gaidajis, Y. Ding, Effect of carbon on the performance of red mud-molten salt composites for thermal management and waste heat recovery applications, J. Energy Storage 44 (2021) 103363, https://doi.org/10.1016/j.est.2021.103363.

[39] L. Zhao, K. Shao, J. Ye, The impact of fiscal decentralization on environmental pollution and the transmission mechanism based on promotion incentive perspective, Environ. Sci. Pollut. Res. 29 (2022) 86634–86650, https://doi.org/10.1007/s11356-022-21762-1.

[40] C.-W. Su, M. Umar, Z. Khan, Does fiscal decentralization and eco-innovation promote renewable energy consumption? Analyzing the role of political risk, Sci. Total Environ. 751 (2021) 142220, https://doi.org/10.1016/j.scitotenv.2020.142220.

[41] Q. He, Fiscal decentralization and environmental pollution: evidence from Chinese panel data, China Econ. Rev. 36 (2015) 86–100, https://doi.org/10.1016/j.chieco.2015.08.010.

[42] Z. Khan, S. Ali, K. Dong, R.Y.M. Li, How does fiscal decentralization affect CO2 emissions? The roles of institutions and human capital, Energy Econ. 94 (2021) 105060, https://doi.org/10.1016/j.eneco.2020.105060.

[43] E. Wang, Q. Cao, Y. Ding, H. Sun, Fiscal decentralization, government environmental preference and industrial green transformation, Sustainability 14 (2022) 14108, https://doi.org/10.3390/su142114108.

[44] C. Xu, Y. Cai, C. Zhou, Y. Qi, The impact of VAT tax sharing on industrial pollution in China, J. Clean. Prod. 415 (2023) 137926, https://doi.org/10.1016/j.jclepro.2023.137926.
[45] I. Ferrara, P. Missios, H.M. Yildiz, Inter-regional competition, comparative advantage and environmental federalism, Canadian Journal of Economics/Revue Canadienne d'économique 47 (2014) 905–952, https://doi.org/10.1111/caje.12098.
[46] S. Ren, M. Du, W. Bu, T. Lin, Assessing the impact of economic growth target constraints on environmental pollution: does environmental decentralization matter? J. Environ. Manag. 336 (2023) 117618 https://doi.org/10.1016/j.jenvman.2023.117618.
[47] R. Liu, X. Zhang, P. Wang, A study on the impact of fiscal decentralization on green development from the perspective of government environmental preferences, Int. J. Environ. Res. Publ. Health 19 (2022) 9964, https://doi.org/10.3390/ijerph19169964.
[48] J. Sheng, W. Zhou, S. Zhang, The role of the intensity of environmental regulation and corruption in the employment of manufacturing enterprises: evidence from China, J. Clean. Prod. 219 (2019) 244–257, https://doi.org/10.1016/j.jclepro.2019.02.113.
[49] T.S. Adebayo, D. Kirikkaleli, Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools, Environ. Dev. Sustain. 23 (2021) 16057–16082, https://doi.org/10.1007/s10668-021-01322-2.
[50] D. Wang, Z. Zhang, R. Shi, Fiscal decentralization, green technology innovation, and regional air pollution in China: an investigation from the perspective of intergovernmental competition, Int. J. Environ. Res. Publ. Health 19 (2022) 8456, https://doi.org/10.3390/ijerph19148456.
[51] T. Ge, W. Qiu, J. Li, X. Hao, The impact of environmental regulation efficiency loss on inclusive growth: evidence from China, J. Environ. Manag. 268 (2020) 110700, https://doi.org/10.1016/j.jenvman.2020.110700.
[52] Y. Ouyang, F. Ye, K. Tan, The effect of strategic synergy between local and neighborhood environmental regulations on green innovation efficiency: the perspective of industrial transfer, J. Clean. Prod. 380 (2022) 134933, https://doi.org/10.1016/j.jclepro.2022.134933.
[53] Z. Tang, H. Yu, J. Zou, Neighbor impacts of environmental regulation: the case of low-carbon pilot program in China, Energy 276 (2023) 127509, https://doi.org/10.1016/j.energy.2023.127509.
[54] Z. Gai, Y. Guo, Y. Hao, Can internet development help break the resource curse? Evidence from China, Resour. Pol. 75 (2022) 102519, https://doi.org/10.1016/j.resourpol.2021.102519.
[55] F. Wang, J. He, Y. Niu, Role of foreign direct investment and fiscal decentralization on urban haze pollution in China, J. Environ. Manag. 305 (2022) 114287, https://doi.org/10.1016/j.jenvman.2021.114287.
[56] N. Nunn, N. Qian, US food aid and civil conflict, Am. Econ. Rev. 104 (2014) 1630–1666, https://doi.org/10.1257/aer.104.6.1630.
[57] D. Ma, Q. Zhu, Innovation in emerging economies: research on the digital economy driving high-quality green development, J. Bus. Res. 145 (2022) 801–813, https://doi.org/10.1016/j.jbusres.2022.03.041.
[58] Y. Wang, Y. Zheng, Spatial effects of carbon emission intensity and regional development in China, Environ. Sci. Pollut. Res. 28 (2021) 14131–14143, https://doi.org/10.1007/s11356-020-11557-7.
[59] F. Meng, Y. Zhao, How does digital economy affect green total factor productivity at the industry level in China: from a perspective of global value chain, Environ. Sci. Pollut. Res. 29 (2022) 79497–79515, https://doi.org/10.1007/s11356-022-21434-0.
[60] Z. Liu, S. Chen, T. Tang, H. Luo, Q. Guan, How public education investment and advanced human capital structure affect regional innovation: a spatial econometric analysis from the perspective of innovation value chain, Socioecon. Plann. Sci. 91 (2024) 101800, https://doi.org/10.1016/j.seps.2023.101800.
[61] G. Wu, N. Riaz, R. Dong, China's agricultural ecological efficiency and spatial spillover effect, Environ. Dev. Sustain. 25 (2023) 3073–3098, https://doi.org/10.1007/s10668-022-02169-x.
[62] F. Han, R. Xie, Y. lu, J. Fang, Y. Liu, The effects of urban agglomeration economies on carbon emissions: evidence from Chinese cities, J. Clean. Prod. 172 (2018) 1096–1110, https://doi.org/10.1016/j.jclepro.2017.09.273.
[63] Y. Xue, C. Tang, H. Wu, J. Liu, Y. Hao, The emerging driving force of energy consumption in China: does digital economy development matter? Energy Pol. 165 (2022) 112997 https://doi.org/10.1016/j.enpol.2022.112997.
[64] K. Li, D.J. Kim, K.R. Lang, R.J. Kauffman, M. Naldi, How should we understand the digital economy in Asia? Critical assessment and research agenda, Electron. Commer. Res. Appl. 44 (2020) 101004, https://doi.org/10.1016/j.elerap.2020.101004.
[65] W. Pan, T. Xie, Z. Wang, L. Ma, Digital economy: an innovation driver for total factor productivity, J. Bus. Res. 139 (2022) 303–311, https://doi.org/10.1016/j.jbusres.2021.09.061.
[66] W. Zhang, X. Liu, D. Wang, J. Zhou, Digital economy and carbon emission performance: evidence at China's city level, Energy Pol. 165 (2022) 112927, https://doi.org/10.1016/j.enpol.2022.112927.
[67] Z. Li, J. Wang, The dynamic impact of digital economy on carbon emission reduction: evidence city-level empirical data in China, J. Clean. Prod. 351 (2022) 131570, https://doi.org/10.1016/j.jclepro.2022.131570.
[68] S. Ren, Y. Hao, L. Xu, H. Wu, N. Ba, Digitalization and energy: how does internet development affect China's energy consumption? Energy Econ. 98 (2021) 105220 https://doi.org/10.1016/j.eneco.2021.105220.
[69] J. Lin, H.-M. Wu, H. Wu, Could government lead the way? Evaluation of China's patent subsidy policy on patent quality, China Econ, Rev. E. 69 (2021) 101663, https://doi.org/10.1016/j.chieco.2021.101663.
[70] L. Li, M. Li, S. Ma, Y. Zheng, C. Pan, Does the construction of innovative cities promote urban green innovation? J. Environ. Manag. 318 (2022) 115605 https://doi.org/10.1016/j.jenvman.2022.115605.
[71] P. Aghion, J. Van Reenen, L. Zingales, Innovation and institutional ownership, Am. Econ. Rev. 103 (2013) 277–304, https://doi.org/10.1257/aer.103.1.277.
[72] S. Rao, Y. Pan, J. He, X. Shangguan, Digital finance and corporate green innovation: quantity or quality? Environ. Sci. Pollut. Res. 29 (2022) 56772–56791, https://doi.org/10.1007/s11356-022-19785-9.
[73] Z. Fang, A. Razzaq, M. Mohsin, M. Irfan, Spatial spillovers and threshold effects of internet development and entrepreneurship on green innovation efficiency in China, Technol. Soc. 68 (2022) 101844, https://doi.org/10.1016/j.techsoc.2021.101844.
[74] J. Zeng, M. Škare, J. Lafont, The co-integration identification of green innovation efficiency in Yangtze River Delta region, J. Bus. Res. 134 (2021) 252–262, https://doi.org/10.1016/j.jbusres.2021.04.023.
[75] F. Fan, H. Lian, X. Liu, X. Wang, Can environmental regulation promote urban green innovation efficiency? an empirical study based on Chinese cities, J. Clean. Prod. 287 (2021) 125060, https://doi.org/10.1016/j.jclepro.2020.125060.
[76] X. Wu, D. Fan, Spatial and temporal evolution characteristics of urban green innovation efficiency in Northeast China, Front. Energy Res. 11 (2023) 1167330, https://doi.org/10.3389/fenrg.2023.1167330.
[77] P. Kuai, S. Yang, A. Tao, S. Zhang, Z.D. Khan, Environmental effects of Chinese-style fiscal decentralization and the sustainability implications, J. Clean. Prod. 239 (2019) 118089, https://doi.org/10.1016/j.jclepro.2019.118089.
[78] X. Chen, C.-P. Chang, Fiscal decentralization, environmental regulation, and pollution: a spatial investigation, Environ. Sci. Pollut. Res. 27 (2020) 31946–31968, https://doi.org/10.1007/s11356-020-09522-5.
[79] L. Eyraud, L. Lusinyan, Vertical fiscal imbalances and fiscal performance in advanced economies, J. Monetary Econ. 60 (2013) 571–587, https://doi.org/10.1016/j.jmoneco.2013.04.012.
[80] W. Zeng, L. Li, Y. Huang, Industrial collaborative agglomeration, marketization, and green innovation: evidence from China's provincial panel data, J. Clean. Prod. 279 (2021) 123598, https://doi.org/10.1016/j.jclepro.2020.123598.
[81] G. Fan, X. Wang, L. Zhang, H. Zhu, Marketization index for China's provinces, Econ. Res. J. 3 (2003) 9–18.
[82] Y. Wang, D. Zhang, Q. Ji, X. Shi, Regional renewable energy development in China: a multidimensional assessment, Renewable Sustainable Energy Rev. 124 (2020) 109797, https://doi.org/10.1016/j.rser.2020.109797.
[83] Q. Hong, L. Cui, P. Hong, The impact of carbon emissions trading on energy efficiency: evidence from quasi-experiment in China's carbon emissions trading pilot, Energy Econ. 110 (2022) 106025, https://doi.org/10.1016/j.eneco.2022.106025.
[84] A. Anwar, N.T.T. Huong, A. Sharif, N. Kilinc-Ata, M. Çitil, F. Demirtaş, Is a green world real or a dream? A look at green growth from green innovation and financial development: evidence from fragile economies, Geol. J. 59 (2024) 98–112, https://doi.org/10.1002/gj.4844.

[85] X. Yang, X. Liu, Path analysis and mediating effects of influencing factors of land use carbon emissions in Chang-Zhu-Tan urban agglomeration, Technol. Forecast. Soc. 188 (2023) 122268, https://doi.org/10.1016/j.techfore.2022.122268.
[86] Y. Zhang, S. Zhang, The impacts of GDP, trade structure, exchange rate and FDI inflows on China's carbon emissions, Energy Pol. 120 (2018) 347–353, https://doi.org/10.1016/j.enpol.2018.05.056.
[87] C. Chen, Does money matter for infrastructure outcomes? The effects of public infrastructure finance on state infrastructure quality, J. Public Budg. Account. Financ. Manag. 29 (2017) 375–408, https://doi.org/10.1108/JPBAFM-29-03-2017-B005.
[88] X. Hao, Y. Li, S. Ren, H. Wu, Y. Hao, The role of digitalization on green economic growth: does industrial structure optimization and green innovation matter? J. Environ. Manag. 325 (2023) 116504 https://doi.org/10.1016/j.jenvman.2022.116504.
[89] X. Fang, D.C. Yen, Demographics and behavior of Internet users in China, Technol. Soc. 28 (2006) 363–387, https://doi.org/10.1016/j.techsoc.2006.06.005.
[90] K. Luo, Y. Liu, P.-F. Chen, M. Zeng, Assessing the impact of digital economy on green development efficiency in the Yangtze River Economic Belt, Energy Econ. 112 (2022) 106127, https://doi.org/10.1016/j.eneco.2022.106127.
[91] F.K.S. Chan, H.K. Chan, Recent research and challenges in sustainable urbanisation, Resour. Conserv. Recycl. 184 (2022) 106346, https://doi.org/10.1016/j.resconrec.2022.106346.
[92] D. Liu, Y. Xie, M. Hafeez, A. Usman, The trade-off between economic performance and environmental quality: does financial inclusion matter for emerging Asian economies? Environ. Sci. Pollut. Res. 29 (2022) 29746–29755, https://doi.org/10.1007/s11356-021-17755-1.
[93] X. Wang, L. Wang, S. Wang, F. Fan, X. Ye, Marketisation as a channel of international technology diffusion and green total factor productivity: research on the spillover effect from China's first-tier cities, Technol. Anal. Strateg. 33 (2021) 491–504, https://doi.org/10.1080/09537325.2020.1821877.
[94] W. Ben Arfi, L. Hikkerova, J.-M. Sahut, External knowledge sources, green innovation and performance, Technol. Forecast. Soc. 129 (2018) 210–220, https://doi.org/10.1016/j.techfore.2017.09.017.
[95] A. Razzaq, A. Sharif, I. Ozturk, M. Skare, Inclusive infrastructure development, green innovation, and sustainable resource management: evidence from China's trade-adjusted material footprints, Resour. Pol. 79 (2022) 103076, https://doi.org/10.1016/j.resourpol.2022.103076.
[96] L. Zhang, R. Mu, Y. Zhan, J. Yu, L. Liu, Y. Yu, J. Zhang, Digital economy, energy efficiency, and carbon emissions: evidence from provincial panel data in China, Sci. Total Environ. 852 (2022) 158403, https://doi.org/10.1016/j.scitotenv.2022.158403.
[97] Jing Lu, Qinglan Xiao, Taoxuan Wang, Does the digital economy generate a gender dividend for female employment? Evidence from China, Telecommun. Pol. 47 (2023) 102545, https://doi.org/10.1016/j.telpol.2023.102545.
[98] P. Goldsmith-Pinkham, I. Sorkin, H. Swift, Bartik instruments: what, when, why, and how, Am. Econ. Rev. 110 (2020) 2586–2624, https://doi.org/10.1257/aer.20181047.
[99] Y. Altunbaş, J. Thornton, Does financial development reduce corruption? Econ. Lett. 114 (2012) 221–223, https://doi.org/10.1016/j.econlet.2011.08.020.
[100] H.-Y. Pan, J.-J. Ren, Q. Zhang, S.-X. Du, Effect of "green technology-institution" collaborative innovation on ecological efficiency—the moderating role of fiscal decentralization, Environ. Sci. Pollut. Res. 30 (2022) 19132–19148, https://doi.org/10.1007/s11356-022-23472-0.
[101] K. Lo, How authoritarian is the environmental governance of China? Environ. Sci. Pol. 54 (2015) 152–159, https://doi.org/10.1016/j.envsci.2015.06.001.
[102] M. Yi, Y. Guan, T. Wu, L. Wen, Y. Lei, S. Xu, How does Chinese-style fiscal decentralization affect green technology innovation? Environ. Sci. Pollut. Res. 30 (2023) 46022–46037, https://doi.org/10.1007/s11356-023-25448-0.
[103] B. Lin, Y. Zhou, Does fiscal decentralization improve energy and environmental performance? New perspective on vertical fiscal imbalance, Appl. Energy 302 (2021) 117495, https://doi.org/10.1016/j.apenergy.2021.117495.
[104] B. Yan, L. Wu, X. Wang, J. Wu, How can environmental intervention work during rapid urbanization? Examining the moderating effect of environmental performance-based accountability in China, Environ. Impact Assess. Rev. 86 (2021) 106476, https://doi.org/10.1016/j.eiar.2020.106476.
[105] X. Wang, T. Zhang, J. Nathwani, F. Yang, Q. Shao, Environmental regulation, technology innovation, and low carbon development: revisiting the EKC Hypothesis, Porter Hypothesis, and Jevons' Paradox in China's iron & steel industry, Technol. Forecast. Soc. 176 (2022) 121471, https://doi.org/10.1016/j.techfore.2022.121471.
[106] J. Zhang, Y. Ouyang, P. Ballesteros-Pérez, H. Li, S.P. Philbin, Z. Li, M. Skitmore, Understanding the impact of environmental regulations on green technology innovation efficiency in the construction industry, Sustain. Cities Soc. 65 (2021) 102647, https://doi.org/10.1016/j.scs.2020.102647.
[107] B. Liao, L. Li, Urban green innovation efficiency and its influential factors: the Chinese evidence, Environ. Dev. Sustain. 25 (2023) 6551–6573, https://doi.org/10.1007/s10668-022-02316-4.
[108] Y. Hao, Y.-F. Chen, H. Liao, Y.-M. Wei, China's fiscal decentralization and environmental quality: theory and an empirical study, Environ. Dev. Econ. 25 (2020) 159–181, https://doi.org/10.1017/S1355770X19000263.
[109] C. Zhang, D. Zhou, Q. Wang, H. Ding, S. Zhao, Will fiscal decentralization stimulate renewable energy development? Evidence from China, Energy Pol. 164 (2022) 112893, https://doi.org/10.1016/j.enpol.2022.112893.
[110] C. Autant-Bernard, J.P. LeSage, Quantifying knowledge spillovers using spatial econometric models, J. Reg. Sci. 51 (2011) 471–496, https://doi.org/10.1111/j.1467-9787.2010.00705.x.
[111] F. Wang, S. Gillani, R. Nazir, A. Razzaq, Environmental regulations, fiscal decentralization, and health outcomes, Energy Environ. (2023) 095830, https://doi.org/10.1177/0958305X231164680.
[112] C.Z. Mooney, Modeling regional effects on state policy diffusion, polit, Restor. Q. 54 (2001) 103–124, https://doi.org/10.1177/106591290105400106.
[113] M. Song, J. Du, K.H. Tan, Impact of fiscal decentralization on green total factor productivity, Int. J. Prod. Econ. 205 (2018) 359–367, https://doi.org/10.1016/j.ijpe.2018.09.019.
[114] G. Petroni, B. Bigliardi, F. Galati, Rethinking the porter hypothesis: the underappreciated importance of value appropriation and pollution intensity, Rev. Pol. Res. 36 (2019) 121–140, https://doi.org/10.1111/ropr.12317.
[115] X. Ji, M. Umar, S. Ali, W. Ali, K. Tang, Z. Khan, Does fiscal decentralization and eco-innovation promote sustainable environment? A case study of selected fiscally decentralized countries, Sustain. Dev. 29 (2021) 79–88, https://doi.org/10.1002/sd.2132.
[116] Y. Sun, P. Gao, A. Razzaq, How does fiscal decentralization lead to renewable energy transition and a sustainable environment? Evidence from highly decentralized economies, Renew. Energy 206 (2023) 1064–1074.