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Original Research

Does Innovative City Construction Promote Digital Environmental Innovation? Evidence from Chinese Invention Patents

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Abstract

Digital environmental innovationn (DEI) emphasizes the integration of digital technology into environmental innovation processes that can drive sustainable development in the era of the digital economy. In China, innovative city construction (ICC) aims to foster innovation through place-based policies. This study examines how ICC impacts DEI under the framework of local government yardstick competition. Based on a new specific measure of DEI and panel data from 292 cities in China from 2004 to 2020, this study investigated the impact and its underlying mechanism using the staggered difference-in-difference method. We find compelling evidence that ICC significantly augments DEI. Specifically, DEI would be up to 40% lower if the city did not have this special status. Mechanistic analysis proves that ICC enhances DEI through three channels: alleviating the distortion of land allocation, strengthening digital agglomeration, and enhancing government financial support for science and technology. Heterogeneity analysis indicates that ICC has a larger impact on DEI in cities with greater local autonomy, higher levels of marketization, and stricter environmental regulation. In addition, ICC promotes DEI in neighboring regions, generating a significant "spillover effect." Finally, ICC can effectively reduce environmental pollution through DEI.

Keywords: innovative city construction (ICC), digital environment innovation (DEI), land resource allocation, digital agglomeration, government financial support

Introduction

With its rapid economic development, China has been facing a series of environmental challenges [1, 2]. In this context, environmental innovation is an important means of achieving economic growth and environmental improvement. Unlike general environmental innovation, digital environmental innovation (DEI), as an emerging model of environmental innovation, emphasizes the process of integrating digital technology into environmental innovation. Thanks to its low search, replication, mobility, tracking, and verification costs [3, 4], digital technology may contribute to the realization of rapid identification of opportunities for environmental innovation and efficient combination of resources, thus

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enhancing the efficiency of environmental innovation. Such innovation is characterized by a 'double externality' [5] since it can both reduce the production of negative environmental externalities and produce positive knowledge externalities [6]. Compared to general environmental innovation, DEI exhibits three distinct traits. First, DEI is indispensable for intangible digital technological and data elements. Second, DEI has a greater externality that is caused by strong knowledge spillover and faster changes in digital technology. Third, for deep integration of digital technology with environmental innovation, DEI greatly requires the penetration and flow of tacit digital knowledge [7]. Overall, DEI is not only a cross-multidisciplinary cutting-edge field of environmental innovation and digital technology but also plays an important role in realizing win–win environmental governance and economic development in the era of the digital economy. Consequently, finding ways to motivate DEI has great theoretical and practical significance, especially for emerging manufacturing countries such as China.

The piloting of innovative city construction constitutes an innovation-driven place-based policy. In 2008, Shenzhen was the first city in China to implement an innovative city pilot policy, and as of 2022, there were already 103 innovative cities in China. Innovative cities take innovation as their goal orientation, and to achieve that, they assemble urban innovation resources, which contribute to improving urban innovation and driving economic development. Accordingly, existing studies have found that ICC is conducive to technological innovation, and others have shown that ICC is helpful for green development [8-10]. ICC is a critical national strategy for driving innovation in cities. DEI integrates digital technology and environmental innovation. It will provide new means for economic development and environmental benefits. Regrettably, however, few studies have explored the impact of ICC on DEI. This leaves the following key questions unanswered: Does ICC promote DEI? What is the underlying mechanism for this effect? What heterogeneous impacts will be generated for different cities? To fill the research gap, we set out to address these questions in this study.

This study aims to investigate the promoting effect of innovative city construction (ICC) on digital environmental innovation (DEI) and its mechanisms, with a focus on the differential impacts across various types of cities. By constructing a DEI index and exploring the theoretical mechanisms of ICC, this research extends the interdisciplinary study of environmental and digital innovation. It provides theoretical support and policy recommendations for emerging manufacturing countries like China to achieve sustainable development in the era of the digital economy.

This study makes several key contributions. First, we developed a DEI (Digital Environmental Innovation) indicator, offering a new perspective on environmental innovation research. Previous studies have typically measured environmental innovation [8, 11-13] and digital innovation [14, 15] separately, leading to a scarcity of empirical research on DEI [16]. To address this gap, we constructed the DEI indicator using textual analysis of patent abstracts [17, 18], thereby broadening the scope of innovation economics and enriching environmental economics research. Second, our study comprehensively analyzes the relationship between ICC and DEI, exploring their interconnectedness. While numerous studies have examined the relationship between ICC and technological [19, 20] and green innovation [21, 22], the impact channels between ICC and DEI remain underexplored [23-26]. We demonstrate how ICC promotes DEI by alleviating land allocation distortions, fostering digital agglomeration, and enhancing government financial support for science and technology. These findings extend the research on ICC's innovative performance, particularly in the context of environmental innovation in the digital economy. Third, we explore the heterogeneity in ICC's impact on DEI performance. Unlike Western countries that focus on industries [27], platforms [28], social capital [29], and finance [30], we find that ICC has a greater impact on DEI in cities with higher local autonomy and marketization, clarifying the boundaries of the institutional effect [31]. Additionally, we observe that innovative cities and environmental regulations have yet to synergize in promoting DEI. Finally, we find that ICC can effectively enhance environmental governance through DEI, further expanding the research on ICC's environmental performance in the digital economy era.

The remainder of this paper is organized as follows: In Section 2, we review the literature on environmental innovation and innovative city policy. In Section 3, we outline our analysis of the theoretical mechanisms. In Section 4, we present our economic model, the construction of the variables, and the data source. Section 5 reports the regression results and offers a brief discussion, including benchmark regression, mechanism analysis, heterogeneity analysis, further analysis, and a robustness test. Section 6 presents our research conclusions, theoretical contributions, policy recommendations, limitations, and future directions.

Literature Review

DEI is the frontier of research in current innovation economics. While the integration of digital technology and environmental innovation has not yet been fully charted in the existing literature, we found a significant body of discussion on both environmental innovation and digital innovation. On the one hand, environmental innovation, as part of the wider topic of sustainable development, has received increasing academic attention in recent years [32-34]. Environmental innovation is a cost-effective way to achieve the dual goals of economic development and environmental protection [5, 35]. Numerous studies have focused on the driving factors of environmental innovation, mainly in terms

of finance, taxation [36, 37], innovation subsidies [38, 39], R&D [40], and environmental regulation [41]. On the other hand, as a popular academic topic in innovation economics, digital innovation underscores the integration of digital technology into the innovation process [42-44], concerning which scholars have made significant progress and produced fruitful results [14, 15, 45]. However, according to our knowledge, there have rarely been empirical studies on DEI, leaving a lack of quantification. Nonetheless, DEI releases digital dividends and is a core driver of sustainable development, thus warranting further study.

Research on innovative cities also provides another literature branch for the discussion of this paper. The innovative city policy is a place-based innovation-oriented policy in China. An innovative city refers to a city whose development is mainly driven by innovative elements, such as technology, knowledge, and human capital [46]. There is a body of research on the innovation effects of ICC [47-50]. Empirical studies have mainly confirmed the positive innovation effects of ICC. For example, Zhang and Wang (2022) [51] found that ICC can significantly promote the advancement of urban innovation through knowledge innovation and transformation efficiency. Moreover, Gao and Yuan (2022) [19] found a long-term positive effect on the innovation performance of ICC through a policy spillover effect. Meanwhile, another branch of research shows that ICC has a positive environmental effect. For example, ICC has been found to promote environmental innovation by improving resource allocation efficiency and adjusting industrial structures [8]. Furthermore, ICC has been shown to have a positive effect on the green total factor of energy efficiency by promoting the innovation of environmental technology [52, 53]. Nonetheless, while the existing literature has explored the innovation effect and the environmental effect of ICC separately, few studies have discussed its internal logical relationship with DEI. Discussion of this link not only enriches the research on the innovation performance of innovative cities but also expands our knowledge of their environmental performance in the era of the digital economy.

Theoretical Mechanisms Analysis

As a vital innovation-oriented place-based policy, ICC is different from traditional Chinese development zone policies. For one thing, the latter aims at economic growth, while the ICC aims at innovation. For another, traditional policies are mainly led and driven by governments, while ICC highlights the coordinating role of the government but also the fundamental role of the market in resource allocation. In this sense, ICC might better boost DEI.

Impact Mechanisms of ICC on DEI

As a new innovation-oriented place-based policy, ICC places S&T innovation as the core driving force of economic and social development. Furthermore, its implementation aligns with China's institutional background of "political centralization and economic decentralization." Driven by this innovative city policy, local governments are encouraged to shift their goal from "competing for growth" to "competing for innovation." Accordingly, they will shift from chasing low-factor prices to pursuing the benefits of innovation. Through this logic, ICC has the potential to promote DEI by alleviating the distortion of land allocation, enhancing digital agglomeration, and strengthening government financial support for science and technology.

Firstly, ICC contributes to alleviating the distortion of land resources. Second-generation federal fiscal theory states that local governments are the major drivers of economic growth [54]. Meanwhile, land resource allocation is a critical component of socioeconomic development in China as well as in other developing countries [55, 56]. Moreover, in the era of the industrial economy, land is an important production factor for industrial firms, and the suppression of industrial land prices provides an essential incentive for local governments to stimulate economic growth. By monopolizing the primary market for land, local governments often acquire exclusive rights to supply construction land. Then, the governments pursue high economic growth by depressing the price of industrial land to attract more external investment. Furthermore, to maintain the balance of local financial budgets, local governments tend to raise the price of commercial and residential land to obtain high premiums. In these ways, excessive government intervention in the land factor market distorts the allocation of land factors [57].

Distorted allocation of land resources caused by the traditional economic growth model is not conducive to environmental digital innovation. Such distorted allocation leaves firms most inclined to seek benefits through low-cost land, which will crowd out the resources for firms' innovation. Moreover, it also increases the probability of corruption and collusion between the government and businesses and worsens the innovation environment, finally suppressing firms' innovative dynamism. Additionally, higher real estate prices also raise the cost of innovation, which is not conducive to the development of DEI. However, ICC, as an innovation-oriented local policy, focuses on the benefits of innovation, meaning it will alleviate the distortions of land resources. To do so, it changes the behavior of local governments, moving away from second-generation fiscal federalism, and promotes a model shift from "competing for growth" to "competing for innovation." Innovation focuses on the agglomeration of innovation resources, represented by human capital, and requires less reliance on physical land than industrial production. Therefore, the ICC may change

the land allocation pattern of large amounts of low-priced industrial land and small amounts of high-priced commercial and residential land, which is formed under the model of pursuing economic growth. Alleviating the distortion of land resources can reduce innovation costs and improve the innovation environment while avoiding the crowding-out effect on firms' innovation activities and, ultimately, promoting DEI.

Secondly, ICC enhances digital agglomeration in pilot cities. Innovative city pilots facilitate the optimization of the market environment, thereby stimulating the vitality of the digital market. Due to the need to rapidly upgrade digital technology, digital entrepreneurship places high requirements on the market environment. Accordingly, effective government capacity is required to support and strengthen markets instead of replacing them [58]. Beyond this, ICC further promotes the transformation of local government functions and the optimization of the business environment, thereby facilitating digital entrepreneurship. For example, ICC takes an "innovative and entrepreneurial environment" as an assessment indicator. Furthermore, innovative cities provide convenient conditions for the registration and enrollment of firms, all of which contribute to attracting new firms. To give another example, ICC focuses on the clustering of high-tech industries. Since high-tech industries are closely linked to the digital economy, their clustering spurs the agglomeration of digital firms. In addition, driven by the pilot policy, many cities have also taken part in the “competition for talents,” competing by offering more resource support and development opportunities [59], thus forming a cluster of information talent. Both the agglomeration of digital firms and information talent promote a knowledge spillover effect and tacit knowledge dissemination, thus enhancing DEI in cities.

Finally, ICC can prompt the government to increase its investment in science and technology. Previously, there was a serious market failure in DEI, which required more government intervention. Oriented toward the "GDP tournament," the yardstick competition of local governments in China has emphasized production rather than innovation. Fortunately, innovative cities attach greater importance to an innovation orientation, which has gradually led to the formation of "innovation tournaments" for local governments. Therefore, the ICC can change the government's investment preference of "production over innovation." This involves the promotion of local leaders, which in China is decided by the upper-level governments based on their performance [60]. When the upper-level governments set an expected target, the lower-level governments tend to announce a target exceeding the average value of their counterparts to avoid falling behind the competition. Thus, ICC takes "the share of local fiscal expenditure on science and technology in local fiscal expenditure" as one of its assessment indicators, and local governments have incentives to compete on it. Theoretically, government support can provide financing and reduce R&D costs. Based on the analysis above, we formed the following two hypotheses for this research:

Hypothesis 1: ICC has a positive impact on DEI.

Hypothesis 2: ICC promotes DEI by alleviating the distortion of land resources, strengthening digital agglomeration, and enhancing government financial support in science and technology.

Heterogeneity Analysis

Local Government Autonomy

The development of urban DEI cannot be separated from government support. The decentralization system ensures a certain degree of autonomy for the local government, which can freely dispense resources to support the implementation of the innovative city policy, thus affecting the development of DEI. In China, fiscal decentralization lies at the core of economic decentralization between the central and local governments. Through fiscal decentralization, local governments can better stimulate urban innovation [59]. In regions with higher local economic autonomy, ICC will receive greater financial support from the local government, which is beneficial to the innovation of the digital environment. However, in areas with low local economic autonomy, local governments have limited financial resources. This may lead to limited financial support for innovation and deteriorate the digital entrepreneurial environment by shifting local governments from offering a "helping hand" to a "grabbing hand." Additionally, in order to obtain more revenue from land, cities with lower fiscal autonomy may produce a higher distortion of the land allocation. As a result, the effect of ICC on DEI may decrease or be offset.

Level of Marketization

There are large regional differences in China's marketization processes. Digital technological innovation is highly dependent on entrepreneurship owing to its short upgrade cycle and great risk. The spirit of entrepreneurship in startup enterprises is vigorous. Regions with higher levels of marketization usually have a good market order, a fair legal environment, and a comprehensive intellectual property protection system. In these areas, it is relatively easy to stimulate digital entrepreneurship. Governments are also more efficient in areas with greater marketization. This contributes to lowering the cost of doing business, thus stimulating entrepreneurship [61] and attracting more digital firms to enter. Moreover, a better market environment also means that the marketization of land is relatively well developed, so the distortion of land resources is relatively lower. These elements will free the channels of the ICC’s promotion of DEI. On the contrary, regions with low marketization levels may have a poor digital entrepreneurship environment and underdeveloped

factor markets, especially for land, both of which negatively impact the incentivizing effect of innovative cities for innovation of the digital environment.

Environmental Regulation

The role of environmental regulation in environmental innovation is controversial. There are two main views, i.e., Porter's theory and cost-following theory. According to the former, regions with strong environmental regulations will increase the cost of pollution for firms and force them to carry out environmental innovation. In the era of the digital economy, stricter environmental regulation may form a synergy with innovative cities that promote firms to develop DEI. However, following the cost-following theory, stricter environmental regulation may increase the cost of environmental governance for firms and crowd out firms' investment in environmental innovation [62]. DEI emphasizes the application of digital technology and needs a high level of digital transformation for enterprises, which requires a substantial investment, especially in its early stage. However, strong environmental regulation often incurs a high cost of environmental governance for firms, and thus, the R&D funds and the investment in digital transformation are crowded out. Finally, the policy effect of ICC on DEI will be weakened. In summary, the impact of ICC on DEI in cities with different environmental regulations is unclear and remains to be further examined.

Based on the analysis above, we developed the following hypotheses:

Hypothesis 3: The role of ICC for DEI is stronger in cities with higher local autonomy.

Hypothesis 4: The role of ICC for DEI is stronger in cities with higher marketization.

Hypothesis 5a: The role of ICC for DEI is stronger in cities with stricter environmental regulations.

Hypothesis 5b: The role of ICC for DEI is stronger in cities with weaker environmental regulations.

The Impact of ICC on DEI in Neighboring Cities

Traditional place-based policies oriented toward economic growth may have a siphoning effect on the neighboring economic resources that is unfavorable for the technological innovation of the neighboring regions. In contrast, as a new type of innovation-oriented spatial policy, ICC will exert radiative effects on DEI in the surrounding areas and work in the following ways. First, in the era of the digital economy, the outcomes of innovation rely increasingly on innovation platforms such as key laboratories, enterprise research and development centers, and incubators, which benefit from ICC. Then, major innovation platforms have strong externalities, which enable neighboring cities to receive spillover effects to public services. Second, the ICC takes on a policy demonstration role. In the era of the digital economy, innovation-driven development has become an important driving force for local economic development. Thus, neighboring cities have the incentive to learn from the successful experiences of innovative cities. For example, the neighborhood will also increase financial support for science and technology and learn from ICC, which will promote their DEI. Third, DEI prioritizes the integration of digital technology into environmental innovation. In this regard, the relatively low cost of digital technological distribution may allow it to be transferred to neighboring regions through

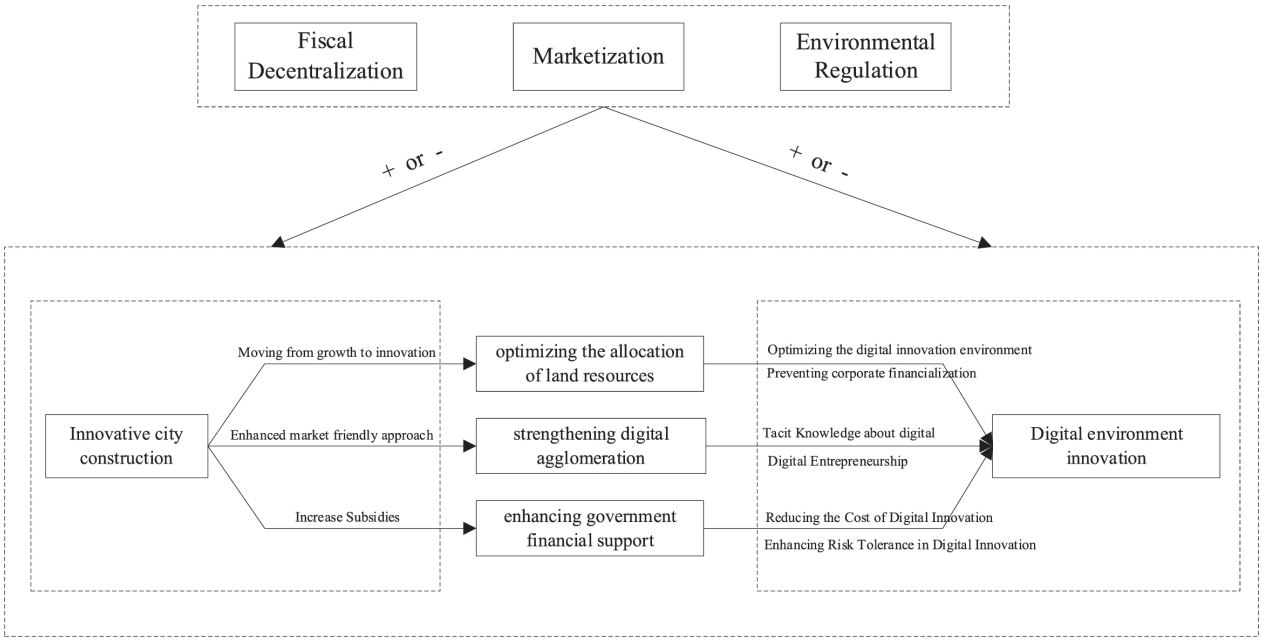

Fig. 1. Dynamic Framework for Impact of ICC on DEI.

various channels, thereby forming knowledge spillover effects. In sum, the above analysis indicates that there are multiple ways in which ICC has a "radiation effect" on DEI in the surrounding areas, leading to the following hypothesis:

H6: There is a "spillover effect" of ICC on DEI in neighboring areas.

Based on the above analysis, we can establish a dynamic framework to represent the influence process of ICC on DEI (Fig. 1). This framework covers, to the fullest possible extent, the influence channels of ICC on DEI and sheds light on the role that heterogeneous urban characteristics play.

Material and Methods

Model

Staggered Differences-in-Differences (SDID) Model

The traditional difference-in-differences (DID) model can only observe the effects of the policy implemented at a single time point. As the innovative city pilot program in China has been gradually rolled out, we chose the staggered differences-in-differences (SDID) model to study the treatment effects of ICC on DEI. The SDID model was set as follows:

$$DEI_{it} = \alpha_0 + \alpha_1 ICC_{it} + \alpha_2 \text{ controls }_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (1)$$

Where i denotes city and t denotes time. *DEI* is the dependent variable of digital environment innovation. ICC is the independent variable, representing an innovative city. Controls denote the control variables. μ and η are the fixed effects of city and year, respectively, which are invariant.

Multiple Pre-Period DID Test

The primary premise of using the SDID model is that the treatment group and the control group of the research samples must have a parallel trend, and this parallel trend cannot change significantly with time. Therefore, we drew on the practice of Beck et al. (2010) [63] and conducted a parallel trend test.

$$DEI_{it} = \gamma + \sum_{k=-13}^{10} \beta_k polic_{i,t_0+k} + \lambda Controls_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (2)$$

Where policy denotes the policy dummy variable and k denotes the kth year of implementation of the innovative city policy.

Mediating Effect Model

In this study, we used the mediating effect model to test the impact mechanism of ICC on DEI. The expressions of this model were as follows:

$$M_{it} = \lambda_0 + \lambda_1 ICC_{it} + \lambda_2 controls_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (3)$$

$$DEI_{it} = \gamma_0 + \gamma_1 ICC_{it} + \gamma_2 M_{it} + \gamma_3 controls_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (4)$$

Where M denotes the mediating variable, and other variables are consistent with the above. λ_1, γ_1, and γ_2 are coefficients, which were the main points of concern in this study. λ_1 reflects the effect of the innovative city pilot policy on the mediating variable. γ_2 reflects the effect of the mediating variable on DEI. If both λ_1 and γ_2 are significant, this means that the mediating effect is established. In short, ICC can influence DEI through the mediating variable.

Spatial Econometric Model

In order to examine the spatial spillover effect of ICC on DEI, we constructed a spatial autoregression model (SAR) (equation (5)), a spatial auto-composite model (SAC) (equation (6)), and a spatial Durbin model (SDM) (equation (7)).

$$DEI_{it} = \alpha_0 + \rho WDEI_{it} + \alpha_1 ICC_{it} + \alpha_2 controls_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (5)$$

$$DEI_{it} = \alpha_0 + \rho WDEI_{it} + \alpha_1 ICC_{it} + \alpha_2 \cdot controls_{it} + \mu_i + \eta_t + \mu_{it}$$
$$\mu_{it} = \lambda W \mu_{it} + \varepsilon_{it} \quad (6)$$

$$DEI_{it} = \alpha_0 + \rho WDEI_{it} + \alpha_1 ICC_{it} + \theta WICC_{it} + \alpha_2 controls_{it} + \mu_i + \eta_t + \varepsilon_{it} \quad (7)$$

Where ρ is the spatial autocorrelation coefficient and W denotes the spatial weight matrix (we used the inverse distance spatial weight matrix). The other variables were the same as in the basic regression model.

Variables

Dependent Variable

The dependent variable in this paper is digital environmental innovation (DEI). The existing literature mainly measures environmental innovation based on environmental patent applications [64-66]. Text analytics is widely used in the fields of economics, finance, and management, and the use of text analytics to determine textual digital features has become a common approach

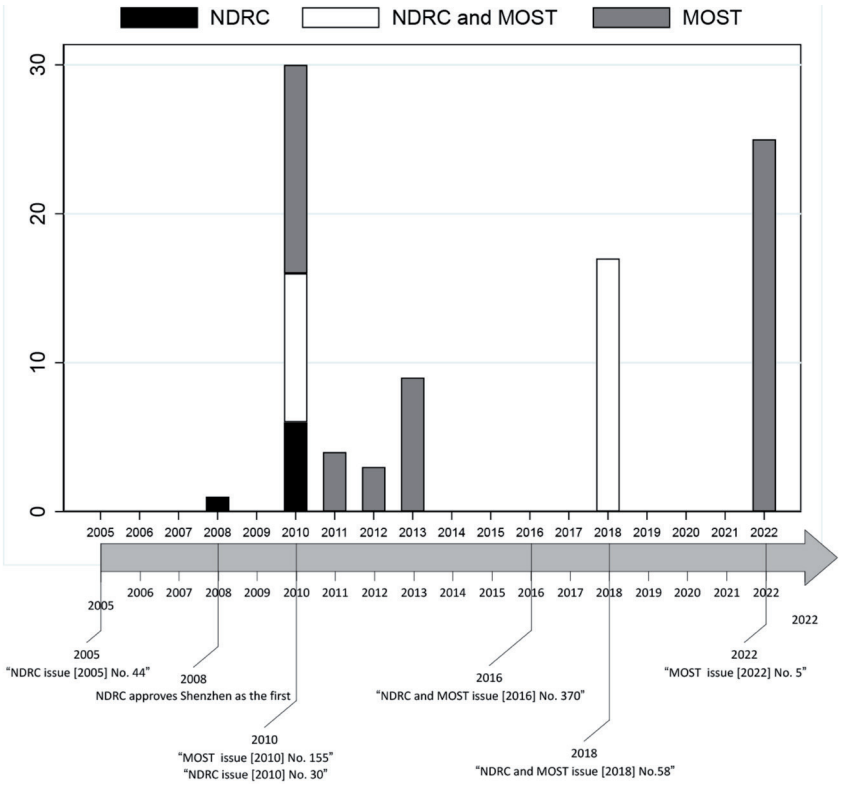

Fig. 2. Development Process of Innovative City Pilot Policy. Note: NDRC stands for the National Development and Reform Commission, and MOST represents the Ministry of Science and Technology.

in academia [67-69]. We used textual analysis to extract digital environmental patents based on keywords relating to digital technology in environmental patent applications. We measured DEI according to the ratio of digital environmental patent applications to the urban population.

Independent Variable

The core independent variable in this paper is whether the city is an innovation pilot city (ICC). If city i is selected as an innovative city in year k, then $ICC_{it} = 1$, if $t >= k$; otherwise, $ICC_{it} = 0$. Fig. 2 illustrates the development of China's innovative city pilot policy. In our study, we used the panel data of 292 cities in China from 2004 to 2020. Considering the availability of data, in regard to whether we could fully measure the implementation effect of innovative city policy, the sample settings were as follows: 72 national innovative pilot cities constructed in batches in 2008, 2010, 2011, 2012, 2013, and 2018 were set as the experimental group, and the remaining 220 cities were set as the control group.

Control Variables

In this study, we controlled for other variables that may affect DEI. The main variables were industrial structure (*ind_stru*), urban population share (*pop*), financial level (*fin*), and industrial firm density (*infd*). Specifically, industrial structure (*ind_stru*) was measured using the share of secondary industry output in GDP. The urban population share (*pop*) was measured by the proportion of the population of the municipal districts to the total population. Financial level (*fin*) was measured by the ratio of the loan balance of financial institutions to GDP. Industrial firm density (*infd*) was measured by the proportion of urban industrial firms to all firms.

Data Source

In this study, we used panel data from the China Patent Database for 292 cities in China from 2004 to 2020. We textually analyzed patents by screening digital keywords based on official government documents to obtain digital environment patent data. City data came from the China City Statistical Yearbook and China Regional Statistical Yearbook. Land data came from the China Land Market Network. Table 1 shows the results of our descriptive statistics for the main variables.

Development Trend of DEI

General Development Trend of DEI

Fig. 3 illustrates the general trend of DEI in China. During the period from 2004 to 2020, DEI was growing rapidly. The share of digital environmental patents in environmental patents was also continuously growing.

Table 1. Descriptive Statistics.

Variable	Num	Mean	SD	Min	Max
DEI	4642	0.170	0.430	0	2.790
ICC	4642	0.130	0.340	0	1
ind stru	4642	0.470	0.100	0.190	0.750
pop	4642	0.360	0.230	0.0600	1
fin	4642	0.910	0.510	0.280	3.060
infd	4642	0.170	0.310	0	1.940

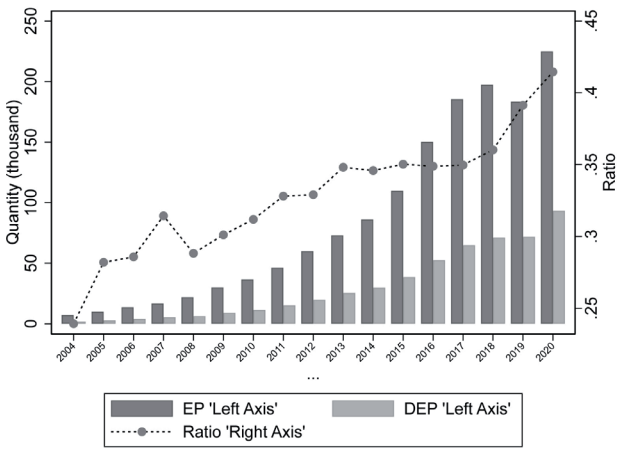

Fig. 3. Changing Trends of DEI. Note: EP denotes the number of environmental patents. DEP denotes the number of digital environmental patents. The dashed line indicates the share of digital environmental patents in environmental patents.

Especially after 2017, the trend was increasing linearly. The share of DEI in 2004 was 23.9%, while it was 41.5% in 2020. This demonstrates that DEI has become a significant part of environmental innovation.

Regional Differences and Spatial Distribution Patterns of DEI

Fig. 4 illustrates the regional distribution differences in DEI. This shows that the eastern region has had a significant advantage in both the number and the percentage of digital environment patents. The possible reason is that the eastern region has a high level of economic development and marketization, so the development trend of DEI has been stronger there. Fig. 5 also demonstrates the spatial distribution pattern of DEI in China in 2004 and 2020. It can be seen that DEI developed faster in the regions selected as innovative cities.

Empirical Results and Discussion

Parallel Trend Test

As shown in Fig. 6, before the policy was implemented, although the average DEI of the treatment group differed from that of the control group, the degree of difference was relatively stable. In other words, the evolutionary trends of the two groups were

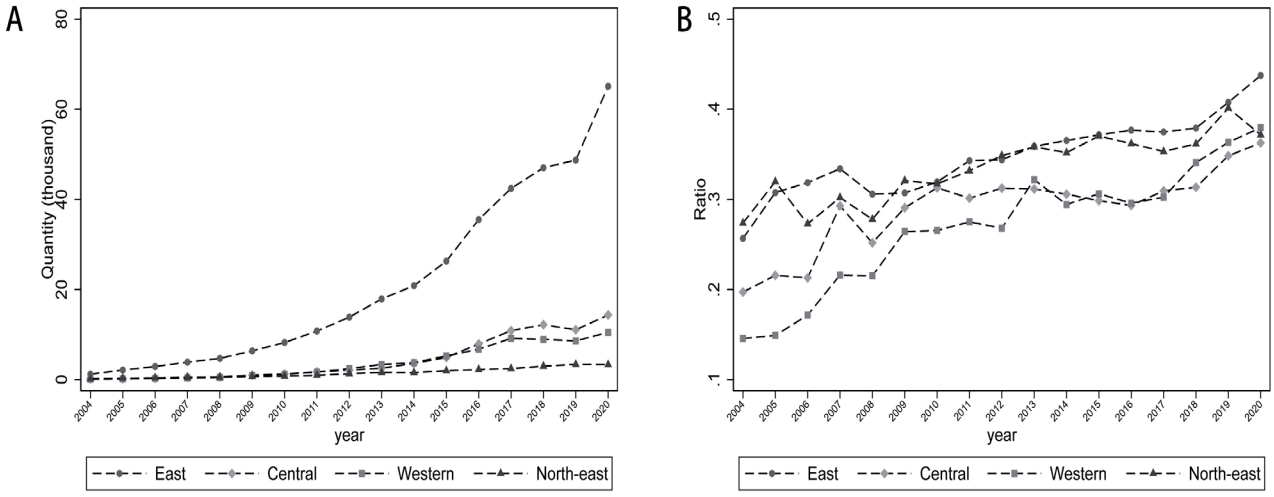

Fig. 4. Regional Differences of DEI. Note: Figure A depicts the "Number of applications of digital environmental patents in different regions" in China; Figure B depicts the "Percentage of applications of digital environmental patents in different regions" in China.

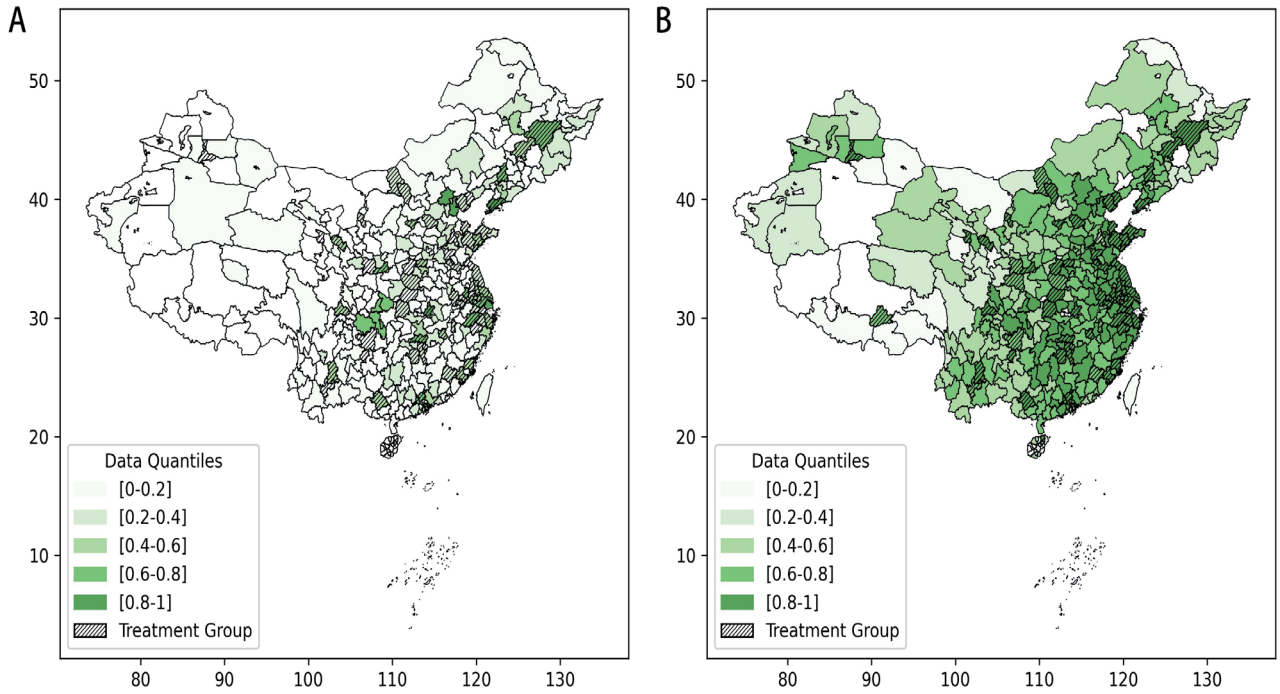

Fig. 5. Spatial Distribution Patterns of DEI. Note: Figure A depicts the "DEI spatial distribution patterns in 2004"; Figure B depicts the "DEI spatial distribution patterns in 2020".

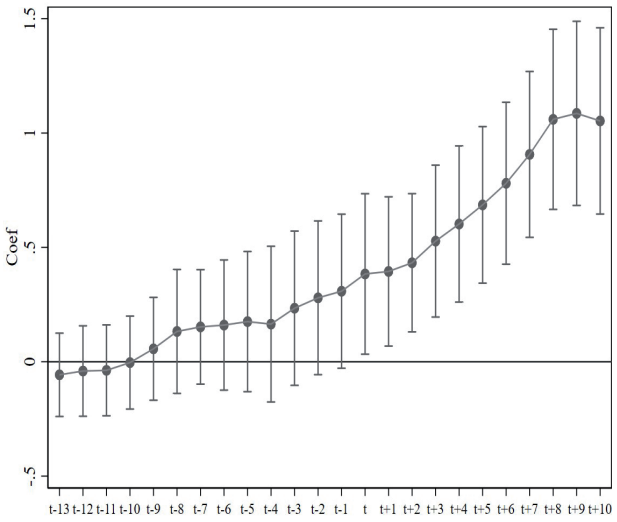

Fig. 6. Parallel Trend Test.

largely the same. Therefore, it could be concluded that the DEI of the treatment and control groups before the implementation of the innovative city policy passed the parallel trend hypothesis test, which was consistent with the premise of the SDID model.

Basic Regression

Table 2 reports the estimated results based on econometric model 1, in which column (1) does not include the control variables, while column (2) does. The empirical results showed that the estimated coefficients of ICC were significantly positive. Specifically, DEI would be up to 40% lower if the city did not have this special status. This indicated that ICC was beneficial to DEI, meaning Hypothesis 1 was verified.

Influence Mechanism

The regression results based on model (1) confirmed the positive impact of ICC on DEI, but the "black box" of the treatment effect was not further revealed. Therefore, the type of transmission mechanism that exists between ICC and DEI became the key issue to be solved in this study. We further investigated the influence mechanism of ICC on DEI from three perspectives: alleviating the distortion of land resources, strengthening digital agglomeration, and enhancing government financial support for science and technology.

Alleviating the Distortion of Land Resources

We used two variables, the ratio of industrial land area and the ratio of industrial land area transferred by agreement, as proxy variables for land resource allocation. Specifically, the ratio of industrial land area was measured by the ratio of urban industrial land area to total urban construction land area (*Inland*). The ratio of industrial land area transferred by agreement was measured by the ratio of urban land area transferred by agreement to the total area of urban construction land (*Atland*). The larger the values of these two variables, the greater the distortion of land resources. Then, we tested the regression results for land resource allocation as a mechanism variable (the estimation results are presented in columns (1) to (4) of panel A in Table 3.

Table 2. The impact of ICC on DEI.

	(1)	(2)
	DEI	DEI
ICC	0.408***	0.405***
	(7.28)	(7.40)
Ind_stru		-0.386***
		(-2.78)
pop		0.088
		(0.39)
fin		-0.064**
		(-2.09)
infd		-0.071
		(-0.28)
City	Yes	Yes
Year	Yes	Yes
N	4642	4642
adj. R2	0.704	0.707

Note: (1) Inside the bracket is the t statistic; (2) "*", "**", and "***" respectively represent significance at the level of 10%, 5%, and 1%.

Columns (1) and (3) show that the estimated coefficients of ICC were significantly negative at the 1% level, suggesting that the innovative city pilot policy was able to inhibit the expansion of urban industrial land. Columns (2) and (4) show that the estimated coefficients of ICC were significantly positive, and the coefficients on both *Indland* and *Atland* were significantly negative, indicating that the innovative city pilot policy can promote DEI in cities by discouraging the expansion of industrial land. In other words, ICC can promote DEI by alleviating the distortion of land allocation.

Strengthening Digital Agglomeration

We measured digital agglomeration in terms of digital firm agglomeration (*Def*) and information talent agglomeration (*Talent*). Specifically, we used the ratio of newly registered digital firms to the urban population to measure Def, and we measured talent using the ratio of information sector employees to all urban employees. Then, we tested the regression results for digital agglomeration as a mechanism variable (the estimation results are presented in columns (1) to (4) of panel B in Table 3. Columns (1) and (3) show that the estimated coefficients of ICC were significantly positive at the 1% level, suggesting that the innovative city policy can promote the agglomeration of digital firms and information talents. Columns (2) and (4) show that the estimated coefficients of ICC were significantly positive, and the coefficients of Def and Talent were significantly positive, suggesting that ICC can promote DEI by fostering the agglomeration of digital firms and information talents.

Enhancing Government Financial Support for Science and Technology

We used the share of S&T expenditures in fiscal expenditures to measure government financial support for science and technology (*Sci*). Then, we tested the regression results for government financial support as a mechanism variable (the estimation results are presented in columns (1) to (2) of panel C in Table 3. Column (1) shows that the estimated coefficient of ICC was significantly positive at the 1% level, indicating that the innovative city policy can promote government financial support for S&T. Column (2) shows that the estimated coefficients of ICC and Sci were both significantly positive at the 1% level, suggesting that ICC can promote DEI by enhancing government financial support for S&T. To sum up, Hypothesis 2 was verified.

Heterogeneity Analysis

The findings of previous studies suggested that ICC can generally contribute to improving urban DEI. However, in China, there are significant differences among cities in terms of resource advantages, degrees of marketization, and environmental regulations. Accordingly, to determine whether the impact of ICC on DEI varied by city, we explored the city heterogeneity of the innovative city policy in this study.

Local Autonomy

We adopted two indicator metrics to measure fiscal decentralization: expenditure decentralization (*EX*) and revenue decentralization (*RE*). Expenditure decentralization is calculated as the ratio of local per capita fiscal expenditure to the sum of local and central per capita fiscal expenditure, while revenue decentralization is calculated as the ratio of local per capita fiscal revenue to the sum of local and central per capita fiscal revenue. We tested the sample for grouping based on the median of *EX* and *RE*, and the results are shown in columns (1) and (2) of Table 4. We found that the coefficients of *EX*×*ICC* and *RE*×*ICC* were significantly positive at the 1% level. This suggested that the positive contribution of ICC to DEI is greater in regions with high fiscal decentralization, which supports the notion of a greater role of ICC for DEI in cities with greater local autonomy. Accordingly, Hypothesis 3 was verified.

Degree of Marketization

We grouped the sample based on the median urban marketization index. Column (1) in Table 5 reports the results of the heterogeneity analysis of the degree

Table 3. Estimation of Influence Mechanisms.

Panel A optimize land allocation				
	(1)	(2)	(3)	(4)
	Indland	DEI	Atland	DEI
ICC	-0.079***	0.373***	-0.031***	0.371***
	(-3.28)	(6.69)	(-3.36)	(6.83)
Indland		-0.169***		
		(-3.14)		
Atland				-0.469***
				(-3.50)
Controls	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	4500	4500	4500	4500
adj. R2	0.748	0.707	0.765	0.708
Panel B strengthen digital agglomeration				
	(1)	(2)	(3)	(4)
	Def	DEI	Talent	DEI
ICC	1.691***	0.250***	0.329***	0.353***
	(7.32)	(5.48)	(3.24)	(6.92)
Def		0.092***		
		(7.52)		
Talent				0.134***
				(4.55)
Controls	Yes	Yes	Yes	Yes
City	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
N	4642	4642	4336	4336
adj. R2	0.650	0.790	0.595	0.722

Panel C enhance government financial support for science and technology		
	(1)	(2)
	Sci	DEI
ICC	0.805***	0.285***
	(6.19)	(6.35)
Sci		0.149***
		(7.27)
Controls	Yes	Yes
City	Yes	Yes
Year	Yes	Yes
N	4639	4639
adj. R2	0.746	0.763

Note: (1) Inside the bracket is the t statistic; (2) "*", "**", and "***" respectively represent significance at the level of 10%, 5%, and 1%; (3) Control variables and fixed effects are not reported.

Table 4. Heterogeneity Analysis 1.

	(1)	(2)
	DEI	DEI
ICC	0.088**	0.005
	(2.25)	(0.14)
EX	-0.030**	
	(-2.40)	
EX×ICC	0.411***	
	(5.55)	
RE		-0.025
		(-1.40)
RE×ICC		0.464***
		(6.47)
Controls	Yes	Yes
City	Yes	Yes
Year	Yes	Yes
N	4213	4213
adj. R2	0.719	0.716

Note: (1) Inside the bracket is the t statistic; (2) "*", "**", and "***" respectively represent significance at the level of 10%, 5%, and 1%; (3) Control variables and fixed effects are not reported.

Table 5. Heterogeneity Analysis 2.

	(1)	(2)	(3)
	DEI	DEI	DEI
ICC	0.159***	0.472***	0.452***
	(2.96)	(7.57)	(7.38)
Market	-0.021*		
	(-1.85)		
Market×ICC	0.212***		
	(3.52)		
Rust		0.000	
		(.)	
Rust×ICC		-0.257*	
		(-1.94)	
Regu			0.040***
			(2.98)
Regu×ICC			-0.130**
			(-2.53)
Controls	Yes	Yes	Yes
City	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	3451	4642	4642
adj. R2	0.777	0.710	0.709

Note: (1) Inside the bracket is the t statistic; (2) "*", "**", and "***" respectively represent significance at the level of 10%, 5%, and 1%; (3) Control variables and fixed effects are not reported.

of marketization. The coefficient of *Market×ICC* was found to be significantly positive at the 1% level, indicating that the innovative city pilots have a stronger facilitating effect on DEI in cities with a higher degree of marketization. In addition, old industrial bases emerged in the period of the planned economy, and these heritage locations have low marketization levels. To account for those, in this study, we constructed a dummy variable in terms of whether the city was an old industrial base or not (old industrial cities were assigned a value of 1, and others were assigned a value of 0). The interaction term between this dummy variable and the policy dummy variable was introduced into the regression model, and the results are shown in column (2) of Table 5. We found that the coefficient of *Rust×ICC* was -0.250, which was significantly negative at the 10% level. This indicated that innovative city policies are better implemented when not in old industrial cities, meaning Hypothesis 4 was verified.

Environmental Regulation Intensity

We used the ratio of investment in pollution control to the industrial output value in each province to measure environmental regulation. Then, we grouped the sample based on the median environmental regulation. Column (3) in Table 5 reports the results of the heterogeneity analysis of environmental regulation. We found that the coefficient of *Regu×ICC* was significantly positive at the 1% level, indicating that innovative city pilots have a significant dampening effect on DEI in cities with higher environmental regulations. In other words, innovative city pilots have a significant facilitating effect on DEI in cities with weaker environmental regulations. From the perspective of the cost-following theory, environmental regulation can have a crowding-out effect on DEI, meaning Hypothesis 5b was verified.

Spatial Effect Analysis

Table 6 reports the results of the spatial model tests. We found that the spatial autocorrelation coefficient, the direct effect, and the indirect effect were all significantly positive in all models. This indicated a positive "spatial spillover effect" of innovative city policy. ICC significantly promoted DEI in the region and positively affected the neighboring regions. As such, Hypothesis 6 was verified.

Further Analysis

DEI is an emerging direction of environmental innovation in the era of the digital economy. Its main purposes are to improve the efficiency of environmental

Table 6. Tests for Spatial Spillover Effects.

MODEL	SARDID	SACDID	SDMDID
	(1)	(2)	(3)
Variable	DI	DI	DI
Main ICC	0.334***	0.302***	0.313***
	(18.585)	(16.927)	(17.762)
rho	3.165***	2.900***	3.043***
	(47.955)	(21.685)	(28.838)
lambda		2.846	
		(20.187)	
LR_Direct ICC	0.356***	0.312***	0.387***
	(17.169)	(16.151)	(14.238)
LR_Indirect ICC	3.507***	1.509***	12.001***
	(3.434)	(3.297)	(3.662)
LR_Total ICC	3.864***	1.821***	12.388***
	(3.745)	(3.907)	(3.756)
Controls	Yes	Yes	Yes
City	Yes	Yes	Yes
Year	Yes	Yes	Yes
N	3145	3145	3145

Note: (1) Inside the bracket is the t statistic; (2) "*", "**", and "***" respectively represent significance at the level of 10%, 5%, and 1%; (3) Control variables and fixed effects are not reported.

innovation, reduce environmental pollution, and realize green development. Accordingly, in this part of the study, we examined the relationship between innovative cities, DEI, and environmental performance. We used CO2 emissions—that is, the ratio of urban CO2 emissions to the urban population—as the proxy for environmental performance. The regression results in columns (1) and (2) of Table 7 and column (2) of Table 2 constitute the mediation effect model that was used to examine the environmental outcome of ICC through DEI. Initially, the coefficient of ICC in column 1 is significantly negative, which demonstrates that ICC reduced CO2 emissions. In addition, the results in column 2 indicate that both ICC and DEI significantly reduced CO2 emissions. Based on these results and the previous finding that ICC significantly enhanced DEI, the conclusion could be drawn that ICC reduced CO2 emissions by enhancing DEI. Additionally, the moderation effect model in column 3 of Table 7 provides further empirical evidence that ICC strengthened the impact of DEI on reducing CO2 emissions. This suggests that the environmental outcomes of continued ICC can help China achieve its carbon peaking and carbon neutrality goals and, ultimately, facilitate green development.

Robust Test

The Multi-Temporal DID Test

Traditional DID may result in samples being identified initially as treatment groups, later becoming control groups for samples, and then being identified as treatment groups, which may occur since samples are not identified as treatment groups at the same time. To alleviate concerns about this issue, we performed a robustness test based on the estimator proposed by Borusyak et al. (2024) [70], and the results are shown in Fig. 7. We found that the parallel trend assumption was satisfied after accounting for heterogeneous treatment effects.

Replace Dependent Variable

In order to ensure the reliability and practicality of the model, we used the patents per capita for DEI (IPC_DEI), calculated according to the IPC classification number, to replace the dependent variable (DEI) in this paper. The results are shown in column (1) of Table 8. We found that the coefficient estimate of ICC was 0.368 and was significant at the 1% level. This suggested that ICC drove the level of DEI. After replacing the dependent variables, the estimation results were

Table 7. Further Analysis.

	(1)	(2)	(3)
	CO2 emission	CO2 emission	CO2 emission
ICC	-1.522***	-1.258***	-0.735***
	(-7.29)	(-5.24)	(-3.72)
DEI		-0.650**	0.289
		(-2.13)	(0.50)
DEI×ICC			-1.411***
			(-2.65)
Controls	YES	YES	YES
City	YES	YES	YES
Year	YES	YES	YES
N	4615	4615	4615
adj. R2	0.962	0.962	0.963

Note: (1) Inside the bracket is the t statistic; (2) "*", "**", and "***" respectively represent significance at the level of 10%, 5%, and 1%; (3) Control variables and fixed effects are not reported.

consistent with the benchmark results, indicating that the conclusions of this study were robust. Furthermore, we took the logarithm of the number of citations to digital environmental patents as another proxy of DEI (DEIC). Column (2) of Table 8 reports the test results, which revealed that ICC could significantly contribute to high-quality DEI in cities.

Change the Sample Interval

Considering the impacts of the COVID-19 pandemic in 2020, we removed the 2020 sample and regressed the model, and the results are shown in column (3) of Table 8. We found that the estimated coefficient of ICC was significantly positive at the 1% level, which was consistent with the findings presented in the previous section, indicating the robustness of our findings.

Removal of Policy Interference

China has implemented the smart city pilot policy since 2012, and so it came into force during the sample period under study. This change may have interfered with the innovation effect of ICC. Therefore, we

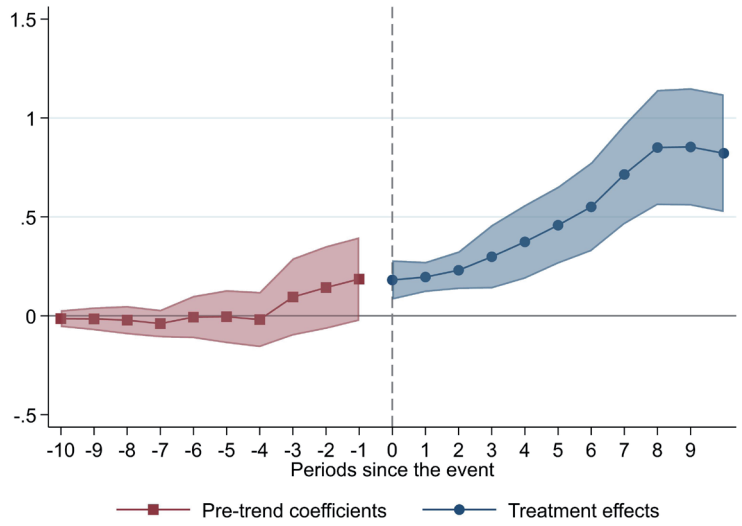

Fig. 7. Multi-Temporal DID Heterogeneity Treatment Effect.

Table 8. Robust Test.

	(1)	(2)	(3)	(4)
	IPC_DEI	DEIC	DEI	DEI
ICC	0.368***	0.404***	0.396***	0.404***
	(5.96)	(4.64)	(7.16)	(7.21)
Smart				0.005
				(0.12)
Controls	YES	YES	YES	YES
City	YES	YES	YES	YES
Year	YES	YES	YES	YES
N	4642	3699	4349	4642
adj. R2	0.675	0.819	0.696	0.706

Note: (1) Inside the bracket is the t statistic; (2) "*", "**", and "***" respectively represent significance at the level of 10%, 5%, and 1%; (3) Control variables and fixed effects are not reported.

included a dummy variable of smart city pilot (*Smart*) in the baseline regression model to control the impact of possible policy interference on the estimation results of this paper. Column (4) of Table 8 reports the regression results. After controlling for smart city policy, we found that the estimates for the innovative city policy remained positive and significant, indicating that the benchmark findings remained robust.

Conclusions

Result

Based on panel data from 292 Chinese cities from 2004 to 2020, in this study, we adopted a staggered DID approach to examine the impact of ICC on DEI. We found that ICC significantly promoted urban DEI by alleviating the distortion of land resources, promoting digital agglomeration, and strengthening government financial support for science and technology. In addition, the impact of ICC on DEI varied between cities. More specifically, the effect of ICC on DEI was more effective in cities with stronger local autonomy, higher degrees of marketization, and weaker environmental regulation. In addition, this paper revealed that innovative city policy has a radiative effect on DEI in the surrounding areas. DEI could also reduce environmental pollution.

Theoretical Contributions

First, this study expands the theoretical perspective on innovation-driven policies. As a new model of urban development, innovative cities place knowledge and technological innovation at the core of urban growth [71]. Unlike the innovation city initiatives in developed Western countries, which are more market-driven [72, 73], China's innovative city construction emphasizes the role of the government [74]. Our research focuses on China's innovation-driven policies, highlighting the expanded role of local governments within these policies. Given the significant regional disparities in China, local governments possess unique informational advantages [75]. The study underscores the crucial role of local governments as the actual implementers of innovation policies within China's system of "political centralization and economic decentralization."

Second, we explain why innovative city construction promotes digital environmental innovation from the theoretical perspective of local government competition. Unlike the general government competition theory, which primarily focuses on "promoting economic growth and increasing fiscal revenue" [31, 76], our findings suggest that as the economic and political gains from "growth" competition diminish, local governments are increasingly competing for innovation. This shift from "race to the bottom" competition, driven by the pursuit of low-cost resources, to "race to the top" competition, driven by the pursuit of innovation gains, is fueling digital environmental technology innovation. Our study opens the black box of the relationship between innovative city construction and digital environmental innovation, validating the effectiveness of this mediating mechanism.

Third, we expand the theory of environmental regulation based on the characteristics of emerging transition economies. Existing research on environmental regulation theory features considerable debate around the Porter hypothesis and the Pollution Haven hypothesis [33, 77]. Our study attempts to deepen the exploration of environmental regulation theory by focusing on the characteristics of digital environmental innovation[16]. We find that local governments' innovation-driven policies have failed to synergize with environmental regulations to promote digital environmental innovation.

Policy Recommendations

First, the practical experience gained from the innovative city pilot should be summarized and improved. Additionally, the tracking, evaluation, and monitoring procedures for the effects of the pilot policy should be further improved in the future. In addition, a flexible selection and exit strategy should be established to remove cities with poor pilot performance from the list of pilot cities. Meanwhile, considering the role of innovative cities in promoting innovation in the digital environment, the number of innovative cities should also be appropriately increased.

Second, the channels for innovative cities to promote DEI should be further developed. Plus, based on those already known, it is necessary to actively promote the marketization of land elements in order to avoid excessive government intervention in land supply. In the future, local governments should continue to standardize their land transfer practices and strengthen the market-based regulation of land transfers, promoting the gradual transition of industrial land from "policy pricing" to "market pricing." Moreover, a suitable business environment should be established for digital firms. For one thing, it is necessary to focus on constructing an urban information infrastructure and strengthen the construction of big data platforms and cloud platforms to gather innovative resources. For another, it is necessary to actively build an innovative R&D platform and strengthen cooperation among firms, universities, and research institutes to create a favorable environment for the DEI of firms. In addition, it is necessary to optimize the structure of fiscal expenditure. Increasing fiscal support for science and technology can improve urban DEI's institutional guarantee.

Third, it is necessary to improve the institutional environment of innovative cities. The impacts of the innovative city pilot policy on DEI in different cities are characterized by different features due to differences in local government resources, levels of marketization, and environmental regulations. Looking to the future, it is necessary to appropriately expand the economic autonomy of local governments so that they have more resources to promote the construction of information infrastructure according to local conditions. Furthermore, market-oriented reform should be expanded to create a favorable market environment for the development of DEI in innovative cities. In addition, actively promoting digital transformation, slowing the adverse impact of environmental regulation on DEI, and forming a joint force of environmental regulation and innovation cities to promote DEI will be valuable steps.

Finally, the role of ICC should be harnessed in driving DEI in the neighboring regions. Innovative cities should work to their own advantage, and based on that, they should spread all kinds of innovative resources and actively promote regional technology transfer to lay the foundation for DEI. In addition, neighboring cities should be actively integrated into the regional technology market, as well as strengthen their cooperation and exchanges with key innovative cities, to increase the opportunities for scientific research cooperation and exchange, establish a sound mechanism for the exchange of regional talents, and better absorb the "spillover effect" of innovative cities.

In sum, the integration of digital technology into environmental innovation actions offers a new research perspective for environmental economics. The main values of this study are as follows: Firstly, examining the impact of ICC on DEI has helped enrich our understanding of how to promote environmental innovation in the digital economy. Secondly, this study has furthered the research related to the impact of ICC on regional innovation from the perspective of local government behavior. In this regard, our conclusions highlight that ICC promotes DEI by alleviating the distortion of land resources, strengthening digital agglomeration, and enhancing financial and technological investment, indicating that ICC brings a new yardstick competition of innovation for local governments. Finally, this paper has presented a comparative analysis of the implementation effects of innovative city policy based on the characteristics of different cities. Such empirical evidence may be used to facilitate the further optimization of innovative urban policy. Future research can extend the findings of this study in three key ways. First, the influence channels of ICC on DEI can be explored in terms of firm-level mechanisms. Second, it is necessary to expand the research scope to newly industrialized countries, which will help with developing general conclusions about the impact of place-based policies on innovation in the era of the digital economy. Third, DEI may be more deeply explored from the perspective of breakthrough innovation.

Limitations and Future Directions

First, regarding research methodology: While we employed advanced machine learning-based textual analysis to construct our research indicators and tested their robustness using various methods, there is still no consensus in the academic community on this approach. Additionally, although we used fixed effects models, which are common in causal analysis, there remains room for improvement. With the development of AI, big data, and 5G, future research could adopt more advanced methodologies for both indicator construction and causal analysis.

Second, regarding the research sample: Our findings are based on data from China's administrative system. While our conclusions offer valuable insights into authoritarian regimes, they may not be generalizable to Western developed countries. Relying solely on Chinese data might limit the universality of our results. Therefore, future research could consider exploring this issue using data from Western developed nations.

Third, regarding the research perspective: Our study examines how innovation-driven policies promote digital environmental innovation from the perspective of local government competition. However, as the digital economy evolves, it not only alters industrial structures but also profoundly impacts social ecosystems. Future research could explore this issue further from the perspective of digital economy theories. Additionally, the innovative city construction we studied represents just one form of innovation-driven policy. Since innovation-driven policies can take various forms in different countries, future research could broaden the scope to investigate multiple types of such policies.

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Conflict of Interest

The authors declare no conflict of interest.

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