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Smart city and green innovation: Mechanisms and industrial emission reduction effect

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ABSTRACT

Green innovation is essential for environmentally sustainable development. The construction of smart cities offers significant potential for developing green innovation through optimizing urban administration and improving the allocation of critical resources. Using Chinese city data from 2005 to 2019, this study adopts a causal identification framework based on the multi-temporal difference-in-difference method to explore the impact of smart city construction on green innovation and the mechanism and joint industrial emission reduction effect between them. A positive and significant relationship with a weak inverted U-shaped trend was found between smart city construction and green innovation. Besides the direct channel, labor factor allocation, venture capital attractiveness, and market accessibility are essential indirect channels between the two concepts. Furthermore, the effects of smart city construction on green innovation varied depending on the marketization level, administrative rank, population size, and geographic location of the city. In addition, the interaction of the two constructs negatively affected industrial emissions, which helped optimize the environment. These findings suggest that smart city construction offers a digital dividend for developing green innovation and creating an efficient, sustainable environment.

1. Introduction

Overindulgence in pollutants can harm the healing capacity of the environment and public health [1,2]. This fact has increased people's awareness of the need for sustainable and green development [3]. Recently, many studies [3–6] have demonstrated that green innovation offers solid technical support for realizing the coordinated development of green economic growth and the environment and boosting core competitiveness in a competitive market [7,8]. This finding proposes underlying solutions for building a sustainable environment. However, sustained and substantial capital investment is required to support the development of technological innovation and environmental sustainability [9,10], which squeezes the resources of city development and makes cities often lack incentives to undertake green technology research and development; this situation slows the process of green innovation development [11].

Fortunately, the introduction of the smart city concept has provided a turnaround. Smart city construction is an overall paradigm shift based on modern information and communication technology to promote smart transformation in cities, which optimizes resource allocation and supports enhancing the efficiency and effectiveness of urban management [12]. Moreover, smart cities deeply imply profound connotations, such as sustainable development [12] and green innovation incidentally [13]. Thus, it seems possible

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that smart city construction is a critical factor in promoting green innovation and development. These have been supported to some extent by some studies. For example, Yang et al. [14] analyzed the positive impact of smart city construction on urban green innovation and found heterogeneity in the subsequent effects. Yan et al. [15] showed that smart city construction can promote urban green technological innovation, and this effect is accompanied by heterogeneity. Studies from Qiu [16], Jiang et al. [17], and Tang et al. [18] obtained similar conclusions. In addition, smart city construction can indirectly play a key role in improving energy efficiency [19,20], promoting industrial transformation [15], reducing pollution emissions and carbon emissions [6,21], and fostering green economic growth with the support of green technologies [4,5].

The literature shows that smart city construction is an essential driver of green innovation and provides an impetus for advancing green development. However, there is still a need for more rigorous empirical evidence to support the relationship among smart city construction, green innovation, and industrial emissions. Based on the theoretical and practical needs of urban smart construction and sustainable development, this study takes a series of smart city pilot policies implemented in China since 2012 as a quasi-natural experiment to evaluate whether smart construction can empower green innovation and green development. It also explores how heterogeneity manifests itself in the light of different city characteristics and identifies what feasible paths are available to promote the exertion of such an effect.

This study adds to the existing literature in the following ways. First, direct evidence of the causal relationship between smart city construction and green innovation was provided. Most established studies argue that smart city construction helps induce technological innovation [22,23]. However, this deduction does not show that smart city construction is favorable to green development because technological innovation does not necessarily lead to green development. Based on the causal identification framework of the multi-temporal difference-in-difference method, this study offers an intuitive and sufficient test of the direct causal link between smart city construction and green innovation. This analysis expands the research on the economic and social effects of smart city construction and the formation factors of green innovation. Compared with existing studies on the relationship between smart city construction and green innovation [14–16,18], this study uses broader samples at city level and conducts more diversified robustness tests with Tobit models, system GMM methods, and other means. More critically, this study examines, from different perspectives, the mechanism channels in which smart city construction affects green innovation and discusses the heterogeneous performance between the two concepts from more dimensions. The conclusions of these analyses provide targeted references for the future promotion of green innovation based on intelligent and digital construction.

Second, the intermediate mechanism of smart city construction affecting green innovation was thoroughly discussed. Existing studies have mainly analyzed the channels through which smart city construction affects green innovation in terms of personnel input, information infrastructure construction, and other channels [16,18]. Different from this approach, this study considers multiple perspectives, such as the internal and external factor allocation and market operation of the city, which is more capable of highlighting the systematic and interactive characteristics of the development of innovation [24]. Using this method, this study explores the potential mechanism of the smart city construction affecting green innovation with the labor force allocation, venture capital attraction, and market accessibility and market structure as three indirect channels. This enriches the theoretical contribution of the present question and analysis and provides an excellent opportunity for more accurate and effective green innovation governance in the future.

Third, the further impact of smart city construction and green innovation on industrial emissions was explored. Whether smart city construction can substantially promote green development cannot be determined directly by focusing only on the relationship between smart city construction and green innovation. Accordingly, considering the fact that industrial activities are the primary source of environmental emissions [25,26], this study takes industrial SO_2 and wastewater as the manifestation of industrial emissions and analyzes the industrial emission reduction effects of smart city construction and green innovation. This understanding can provide more distinctive evidence to validate the green innovation and industrial emission reduction effects of smart city construction, which further strengthens the practical significance of this study.

2. Background and hypothesis

2.1. Policy background

The smart city concept originated from the “Smart Earth” concept proposed by IBM in 2008 [27]. A smart city is a new form of city that is constructed with the goal of more scientific development, more efficient management, and better life; it is supported by information technology and communication technology through transparent and sufficient information access, extensive and safe information transmission, and practical and scientific information processing; this concept aims to improve the efficiency of urban operation, enhance the level of public service, and form intelligent and sustainable development [12].

Slightly later, China officially started the construction of smart cities through pilot projects in 2012 and announced three rounds of pilot projects in 2012, 2013, and 2014. These projects cover more than 200 prefectural- and county-level cities. China has gradually built up a complete institutional framework of smart city policies, including the overall strategic deployment, construction standards, implementation paths, and evaluation systems. This initiative aims to alleviate the adverse problems caused by the rapid development of urbanization, such as the environment, energy use, and transportation; promote the intelligent and green development of cities for enhancing their aggregation and radiation-driven roles; and improve the management efficacy and comprehensive competitive advantages. Given that green innovation included in the connotation of smart cities is an essential driving force of green development, smart city construction offers an unparalleled opportunity to promote green innovation [13,15]. The implementation of smart city pilot policy in China provides an excellent quasi-natural experiment to assess the role of smart city construction on green innovation and industrial emission and explore the intermediate mechanism among them.

2.2. Research hypotheses

The construction of smart cities affects the development of green innovation through direct and indirect channels. The direct channel between them lies in the fact that smart city construction can strengthen the flow and accumulation of knowledge in the city, enhance the role of market feedback in supporting green innovation, and expand the space for green innovation development [23]. On the one hand, innovation mainly originates from the recombination of existing knowledge [28], and cities are spatial carriers of knowledge generation, dissemination, and accumulation. Smart city construction can strengthen the improvement of information infrastructure in the city [16], which reduces the cost of intra- and inter-city communication and improves communication efficiency. This situation prompts the city to promote the absorption of external knowledge through effective research exchanges and cooperation; it also increases the possibility of knowledge recombination, which accelerates the speed of innovation [29]. Moreover, the low knowledge retrieval and learning costs brought about by the development of digital infrastructures have significantly broadened the boundaries of knowledge acquisition and flow. This expansion enhanced the possibilities of knowledge search and extraction across technological domains, increased the frequency of interactions across regions [30], and contributed to the reorganization of old ideas and the generation of new ones [31]. In addition, digital transformation driven by smart city construction helps improve innovation quality and enhance the ability to absorb and transform knowledge [32], which provides a new impetus for green innovation.

On the other hand, green development has gradually become a consensus, which enormously stimulated consumers' green and environmental preferences [3]. The construction of smart cities has led to the broader popularization and application of big data and other digital means, and the information has become more transparent and open [33]. Thus, producers collect data from the consumer side to portray and interpret consumer behavior laws more efficiently, which enables accurate prediction of consumer demand and preferences and eases observation of market demand [34]. Moreover, the faster dissemination of information also facilitates rapid consumer feedback, which allows producers to utilize the "wisdom of the crowds" for accelerating technological iteration; this utilization indirectly contributes to increased innovation efficiency and performance [35]. These processes will also generate new data, which provides new elements to the innovation process and supports green innovation development [36].

Smart city construction also indirectly affects green innovation through three paths: first is through optimizing the channels for labor factor allocation. Human capital and intellectual capital are critical drivers of innovation development [37], and distorted labor allocation leads to waste of resources and brain drain. This situation in turn inhibits R&D activities, leads to lock-in effects on technological development, and even exacerbates air pollution [38]. Therefore, reasonable labor allocation is crucial in the green R&D process. Smart cities supported by emerging technologies, such as the Internet of Things, big data, and cloud computing, can optimize resource allocation more scientifically and accurately, improve the utilization efficiency of resources, and strengthen the management of urban resources [39]. Furthermore, the incubation of smart cities may facilitate the integration of digital technologies with traditional industries, which induces the creation and development of new businesses and sectors and generates new employment opportunities [21,40]. Such development also shows a guiding effect on enabling the labor force to find more suitable jobs with increased access to information, which in turn improves the efficiency of labor allocation and corrects the distortion of factor allocation [41]. It also guarantees the development of green innovation through human capital supply and optimization [15].

Second is the venture capital attraction channel. The R&D process of green innovation requires a large amount of capital investment as support [9]. However, public funds and traditional financing channels are often insufficient to provide adequate support [10], and the resulting lack of incentives for innovation is not conducive to the successful implementation of innovative activities [11]. Not only that, but the mismatch of capital resources will weaken the allocation efficiency of capital and exacerbate the bottleneck of technological development [42]. Introducing venture capital will provide more support for green innovation development and accelerate the process of technological change [25,43], which is also vital for achieving sustainable development [25,10]. Smart city construction provides an excellent opportunity for the introduction of venture capital. Specifically, the construction of smart cities, supporting by information and communication technologies, helps build a more inclusive and resilient development environment; such an environment creates opportunities and induces the development of green innovation [44]. These potential opportunities will attract more venture capital, which leads to the cyclic causality between venture capital and innovation [45]. This situation reinforces the positive impact of venture capital on green innovation.

Third is through the channel of market accessibility and market structure. The market is a powerful mechanism for disseminating and utilizing knowledge and information for innovation, which constitutes an intermediary channel for smart city construction affecting green innovation. On the one hand, digitization and intelligence have been developed rapidly with smart city construction, which significantly decreased the search and learning costs of knowledge and information. This situation provides the breadth of connectivity and the convenience of information for market players and decreases the threshold of innovation participation [46], which is conducive to breeding an open urban innovation ecology and promoting green innovation through the agglomeration effect [14]. On the other hand, the rapid rise in digital technology represented by the Internet has allowed transactions formed through e-commerce to be enabled by technologies that not only bring innovations in processes and business models [47] but widen the boundaries of the market [48]. Such integration provides opportunities and incentives for firms to establish and grow. The superposition of the increase in the number of market players and the effect of accelerated information dissemination and widening of the scope of dissemination brought about by the construction of smart cities helps enterprises enhance the learning of knowledge and information about the external environment and become more aware of the market trends of their competitors. By integrating market information and applying it to optimize production decisions, enterprises will significantly strengthen the atmosphere of imitation, competition, and cooperation in the market of the same industry [49]. This setting will encourage enterprises to establish a development advantage through innovation [7], especially green innovation that is more in line with the current reality of the green development needs. Such a setting will indirectly reinforce the willingness of new and incumbent firms to invest in green innovation

[50], which exerts a positive impact on the development of green innovation.

In addition to the green innovation effect, smart city construction's industrial emission reduction effect is also crucial. Smart cities coincide with green innovation, which reduces industrial emissions in three points. First, digitalization driven by smart city construction is crucial for achieving environmental innovation transformation [51], and continuous investment in green innovation mitigates ecological degradation [52]. The application of green technologies, along with real-time monitoring systems of smart cities, improves the supervision of environmental pollution and access to pollution information [53]. This application improves resource efficiency and reduces pollution treatment costs, which is the primary prevention of environmental pollution in urban enterprises and its management. Such improvements reduce industrial emissions and promote green environmental transformation [13]. Second, green technology combined with the enhanced information technology means of smart cities makes enterprises close to market demand by enabling the continuous in-depth exploration of consumer demands, optimizes past business patterns, stimulates green product innovation, and improves resource allocation efficiency by reducing the backward production capacity through the "catfish effect" [8]. Third, the construction of smart cities and the widespread use of green technologies facilitate the transformation and upgrading of traditional industries and industrial structures out of low energy consumption and low emissions [15], which reduce energy consumption and pollution emissions and ultimately promote green development [54]. This transformation also reshapes factor input and allocation structure, which further energizes the efficiency of the green economy.

Following this theoretical analysis, the diagram of the conduction mechanism is shown in Fig. 1, and three hypotheses are formulated herein.

Hypothesis 1. Smart city construction generally promotes green innovation.

Hypothesis 2. Smart city construction impacts green innovation by alleviating labor allocation distortions, strengthening venture capital investment, and enhancing market accessibility, among other indirect channels.

Hypothesis 3. Smart cities and green innovation collaborate to curb industrial emissions.

3. Method and data

3.1. Model selection

Smart city pilot policy in China is divided into multiple rounds and implemented extensively, which is an excellent quasi-natural experiment for this study. A multi-temporal difference-in-difference model, which is a powerful tool for conducting policy evaluations to obtain accurate estimation results, was applied for the analysis to explore the impact of smart city building on green innovation. Eq. (1) shows the estimation model for the benchmark analysis:

$$gpatent_{it} = \alpha_0 + \alpha smartcity_{it} + \beta X_{it} + \mu_i + \varepsilon_{it} \tag{1}$$

where $gpatent_{it}$ is the level of green innovation. $smartcity_{it}$ is the smart city pilot policy. X_{it} denotes a set of control variables. α_0, α, and β indicate the constant terms, the effects of smart city construction on green innovation, and the coefficients of control variables, respectively. μ_i represents the city characteristics that do not vary over time, and ε_{it} denotes random errors.

3.2. Variables

3.2.1. Dependent variable

Green innovation (*gpatent*). The number of green patent applications was used to characterize green innovation. The classification of green patents published by WIPO eases the identification and isolation of the green innovation component from the overall innovation development. Moreover, patent data can portray the intensity and output of R&D activities in specific technology areas [55]. Specifically, the number of patent applications for green inventions (plus one that took logarithms) was used to indicate the level of green innovation.

In addition, this study adopted the number of green-granted invention patents (with one added and the logarithm taken) as another measure of green innovation, which is demonstrated in the robustness analysis. At the same time, considering a time lag in patent

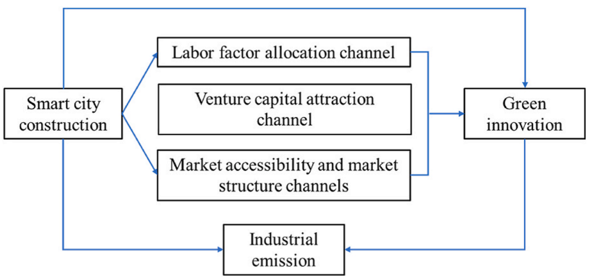

Fig. 1. Transmission channels among smart city construction, green innovation, and industrial emission.

granting (about 2 years), this variable is lagged by two periods when used.

3.2.2. Independent variable

Smart city construction (*smartcity*). The Ministry of Urban and Rural Construction of China announced three rounds of smart city pilot lists in 2012, 2013, and 2014, respectively. This study organized the dummy variable of smart city pilot policy based on the announced lists and the pilot time to indicate the process of smart city construction.

3.2.3. Mechanism variables

Labor allocation distortion (*abstaul*). Referring to the study of Aoki [56], this study calculated the labor mismatch index using the employment and economic output variables to reflect the level of labor allocation distortion. At the same time, this study took the absolute value of the calculated results to be processed to make the direction of the regression consistent due to two cases of under-allocation and over-allocation of resources.

Venture capital level (*vcpe*). The number of venture capital and private equity projects can better reflect the attraction of the city and its access to venture capital. Thus, it was used to react to the venture capital level of the city. The data were selected from China's Regional Innovation and Entrepreneurship Index Construction and Spatial Pattern: 1990–2020 (Reported by Peking University).

Market accessibility and market structure (*newfirm*). The number of new entrants reflects not only the market development potential, business environment, and resource attractiveness of the city but also the market structure. Therefore, the number of new firms was used to measure market access and market structure indirectly. The raw data were extracted from China's Regional Innovation and Entrepreneurship Index Construction and Spatial Pattern: 1990–2020 (Reported by Peking University).

3.2.4. Green development: the industrial emissions

SO_2 emissions (*so2*). Referring to Luo et al. [6], this study reflected the incremental level of waste gas pollution with industrial SO_2 emissions to assess the emission reduction effect of smart city construction and green innovation.

Wastewater emission (*wastewater*). Water resources are integral to green development [57]. Thus, the industrial wastewater discharge situation is also worthy of attention. This study used industrial wastewater emission to measure the incremental level of wastewater.

3.2.5. Control variables

According to previous studies [17,18], a log of urban GDP per capita (*lnpgdp*), secondary industry share (*indus*), the number of higher education students per 10,000 people (*edu*), log of fixed asset investment per capita (*lnasset*), log of local government public expenditure in education and science and technology (*lngov*), and the ratio of foreign direct investment to GDP in the city (*fdi*) were taken as control variables to measure the level of economic development and industrial structure of the cities, factor endowment, level of government innovation support, and degree of external technology introduction. Year and city effects were also used for control.

Furthermore, innovative city construction can help promote green innovation [58], and low-carbon policy can strengthen green innovation R&D and enhance environmental sustainability [59]. Thus, the innovative city policy (*innocity*) and the low-carbon policy (*lowcarbon*) were also taken for control in the robustness test and mechanism analysis section, respectively, to exclude these potential problems of interference. The two variables are dummy variables organized according to the relevant circulars of the Chinese Development and Reform Commission and the Chinese Ministry of Science and Technology.

3.3. Data

This study examined smart city construction, green innovation, and their industrial emission reduction effects following a dataset of

Table 1
Variables and data sources.

Variable	Definition	Data source
gpatent	Logarithm of patent applications for green inventions	China National Intellectual Property Administration
gpatent_g	Logarithm of patents granted for green inventions with a two-period lag	China National Intellectual Property Administration
smartcity	Dummy variable for whether the policy was in place in the current year	Chinese Ministry of Housing and Urban-Rural Development
abstaul	Labor mismatch index by Aoki (2012)[56]	China Urban Statistical Yearbooks
vcpe	Number of venture capital and private equity projects	Peking University
newfirm	Number of new entrants	Peking University
so2	Industrial emissions of SO_2 (ton)	China Urban Statistical Yearbooks
wastewater	Industrial emissions of wastewater (10, 000 ton)	China Urban Statistical Yearbooks
lnpgdp	Logarithm of urban GDP per capita	China Urban Statistical Yearbooks
indus	Secondary industry share (%)	China Urban Statistical Yearbooks
edu	The number of higher education students per 10,000 people	China Urban Statistical Yearbooks
lnasset	Logarithm of fixed asset investment per capita	China Urban Statistical Yearbooks
lngov	Logarithm of the local government's public expenditure in education and science and technology	China Urban Statistical Yearbooks
fdi	Ratio of foreign direct investment to GDP in the city	China Urban Statistical Yearbooks

281 Chinese prefecture-level cities from 2005 to 2019. Raw data on green innovation represented by green patents were extracted from the China National Intellectual Property Administration, and green patents were screened according to the IPC GREEN INVENTORY published by WIPO and then compiled separately. Data on smart city construction were compiled from the Chinese Ministry of Housing and Urban–Rural Development. Information on the remaining variables was extracted from the China Urban Statistical Yearbooks and Peking University, with all value variables deflated based on 2003. Table 1 shows the variables and data sources.

4. Result

4.1. Baseline estimates

Table 2 shows the results of the baseline analysis based on Eq. (1). Smart city construction shows a significant contribution to green innovation, with a coefficient of 0.1015 shown in column (4), which can be significant at a confidence level of 1 %. This finding coincides with those of Tang et al. [18] and results from other studies: the potential channel is due to the information interconnection from smart city construction, which strengthens the learning effect within and among cities and enhances the possibility of transforming knowledge into innovation to promote talents and capital concentration and execute elemental support. This excellent development expectation stimulates further investment by investment institutions. In addition, smart city construction create a good innovation atmosphere that attracts new enterprises and strengthens market competition and cooperation; such an environment forces enterprises to improve their innovation capabilities and indirectly promotes the development of green innovation [50].

4.2. Parallel trend and dynamics of the relationship

The parallel trend assumption is needed for estimation using the difference-in-difference approach. This test was performed using the event study method, with the 8th to 10th period before the policy pilot taken as the baseline group. The model was set up as follows:

$$gpatent_{it} = \alpha_0 + \sum_{k\geq -7}^{6} \alpha_k D_{it}^k + \beta X_{it} + \mu_i + \varepsilon_{it} \tag{2}$$

where D_{it}^k is the smart city pilot dummy variable with the following definition: when the difference between t and the pilot year is k, then $D_{it}^k = 1$; otherwise, the value is 0. α_k becomes the corresponding coefficient.

Fig. 2 shows the estimation results for the parallel trend test and the dynamic effects based on Eq. (2). Before the execution of the policy, no significant policy effect existed on green innovation (as demonstrated by the insignificant coefficients of *rpre7*, *rpre6*, …., *rpre1*), and the parallel trend hypothesis was therefore satisfied. However, after its implementation, the effect of smart city construction on green innovation showed a weak inverted U-shaped trend (shown by the significant and varying coefficients after *rcurrent*). Specifically, the intensity of the effect first strengthened and then weakened. This effect may not be sustained in the long run because the impact started disappearing after the 6th policy implementation period.

This result is probably due to that implementing smart city policy can bring advantages such as lower information and knowledge acquisition costs, optimal labor allocation, and increased venture capital to develop green innovation, which can contribute to improving green innovation. However, in the long run, a subsequent change has not been observed in the city's innovation capacity, which is a critical factor for green innovation [60]. Meanwhile, the increased risk of free-riding behaviors due to innovation spillovers dampened incentives to innovate [61]. Therefore, smart city construction has difficulty playing its role in promoting green innovation.

4.3. Robustness tests

The following robustness tests were also performed to affirm the reliability of the findings.

First is the placebo test. A placebo test for additional analysis was utilized to exclude the interference of unobserved factors, drawing on Li et al. [62]. The policy variable *smartcity* was re-randomized first, and Eq. (1) was re-estimated, with the distribution of

Table 2
Baseline estimation.

VARIABLES	(1)	(2)	(3)	(4)
	gpatent	gpatent	gpatent	gpatent
smartcity	1.9228***	0.4693***	0.4302***	0.1015***
	(45.4536)	(14.0688)	(12.9229)	(3.2250)
Control variables	NO	YES	YES	YES
Time fixed	NO	NO	NO	YES
City fixed	NO	NO	YES	YES
Observations	4215	4178	4178	4178
R-squared	0.339	0.739	0.742	0.814

Note: The t-statistics shown in parentheses ***, **, and * denote significance at the 1 %, 5 %, and 10 % levels.

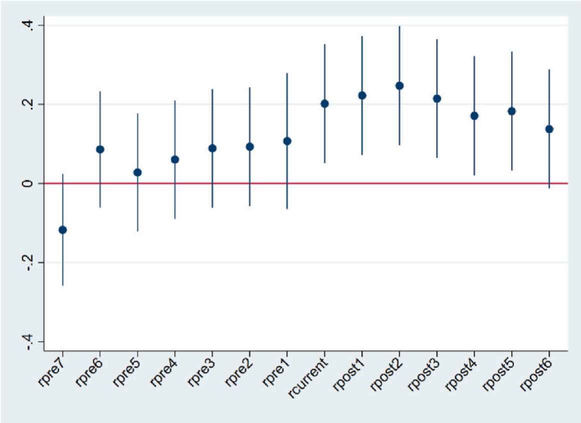

Fig. 2. Parallel trend and dynamic effect test
Note: The figure shows the 95 % confidence interval. *rpre7*, *rpre6*, …., *rpre1* represent 7 periods, 6 periods, …., 1 period before the policy implementation; *rcurrent* represents current period of the policy implementation; rpost1, rpost2, …., rpost6 represent 1 period, 2 periods, …., 6 periods after the policy implementation.

the coefficients after 500 repetitions shown in Fig. 3. The estimated coefficients roughly obeyed a normal distribution with a mean close to 0, which indicates that the unobserved factors did not substantially affect the findings.

Second is the PSM–DID test. The PSM–DID method was used to exclude the interference of selectivity bias. Logit estimation matched the control variables according to the 1:2 caliper nearest neighbor matching principle (with a caliper of 0.05). The results of re-estimation based on support samples are shown in column (1) of Table 3. The estimation results show that the coefficient on smart city construction remains positive, which means that selective bias did not significantly impact the results.

Third is estimation using the Tobit model. The results estimated using the Tobit model, which deals with the sample interception issues, are shown in column (2) of Table 3. The coefficient of smart city policy construction (*smartcity*) differs only in the absolute magnitude of that in the baseline analysis, which suggests that the conclusions of the baseline analysis are reliable.

Fourth is estimation excluding other policy interferences. Before implementing the smart city policy, China had already implemented an innovative city pilot policy from 2008, which has had a significant positive impact on the development of green innovation [58]. Estimation results controlling for innovative city policy are shown in column (3) of Table 3, which are consistent with the conclusions in the baseline analysis.

Fifth is replacing the dependent variable. The measure of green innovation is replaced using the number of green granted invention patents (plus one to take the logarithm) lagged by two periods, while the control variables are lagged by two periods to ensure time consistency. The re-estimated results are shown in column (4) of Table 3, with a positive effect of smart city construction on green innovation at the significance level of 1 %.

Last is estimation excluding endogenous problems. For possible problems such as reverse causality and omitted variables, Eq. (1) was rewritten with a lag of green innovation term and then estimated in differential GMM methods. The results in Table 4 show that the endogeneity problem did not affect the results of the study. In addition, the significant coefficients on one- and two-period lag terms of green innovation (0.4815 and 0.1394, respectively) indicate that cities with an excellent previous green innovation base are more

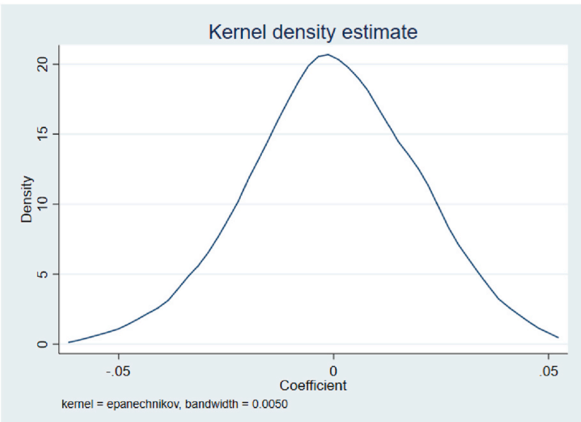

Fig. 3. Placebo test.

Table 3
Robustness tests.

VARIABLES	(1)	(2)	(3)	(4)
	gpatent	gpatent	gpatent[a]	gpatent_g[b]
smartcity	0.2033***	0.1227***	0.0599*	0.1923***
	(4.4535)	(3.9088)	(1.8593)	(5.6434)
innocity			0.2321***	
			(5.6300)	
sigma_u		1.0738***		
		(20.8437)		
sigma_e		0.5278***		
		(87.4926)		
Control variables	YES	YES	YES	YES
Time fixed	YES	YES	YES	YES
City fixed	YES	YES	YES	YES
Observations	3307	4178	4178	3653
R-squared	0.670		0.815	0.695

Note: The t-statistics shown in parentheses ***, **, and * denote significance at the 1 %, 5 %, and 10 % levels.
[a] The significance level can be improved to 1 % using the differential GMM method.
[b] Notably, *smartcity* and control variables are lagged by two periods.

willing to conduct green innovation. This observation coincides with the dependence on inventions and the need to accumulate expertise for innovation [28].

4.4. Transmission channels tests

Further empirical testing was conducted on the transmission channels, which was elaborated on the previous theoretical analysis discussion on the impact of smart city construction on green innovation. The corresponding estimated results are shown in Table 5.

The estimation results show that labor allocation distortion (*abstaul*), venture capital (*vcpe*), and market accessibility and market structure (*newfirm*) all constitute the mechanism channels of smart city construction affecting green innovation. Among them, smart city construction helps alleviate labor allocation distortion, while labor allocation distortion (*abstaul*) negatively affects green innovation (column (2)). This result suggests that smart city construction positively affects green innovation directly and inhibits an indirect effect on green innovation by smoothing out labor allocation distortions. Moreover, the results in columns (3) and (4) suggest that venture capital can act as an indirect channel in which smart city construction influences green innovation by generating positive green innovation. Similarly, the results shown in columns (5) and (6) indicate that the implementation of the smart city policy not only directly affects green innovation but also changes the competition and cooperation in the market by facilitating the market accessibility, which in turn reinforces the positive impact on green innovation.

4.5. Heterogeneous tests

The heterogeneous effects of green innovation in smart city construction in terms of city population size, administrative level,

Table 4
Endogeneity problem treatment and time lag effect test.

VARIABLES		Differential GMM method	
	(1)	(2)	(3)
smartcity	0.5952***	0.4919***	0.4877***
	(5.4950)	(4.9878)	(4.9361)
L.gpatent	0.4105***	0.4815***	0.4699***
	(7.4503)	(8.1783)	(7.8509)
L2.gpatent		0.1394***	0.1246***
		(4.1692)	(3.5684)
L3.gpatent			0.0542
			(1.5271)
Control variables	YES	YES	YES
Time fixed	YES	YES	YES
City fixed	YES	YES	YES
AR (1)	0.000	0.000	0.000
AR (2)	0.376	0.128	0.626
Hansen	0.130	0.248	0.268
Observations	2773	2211	2211

Note: t-statistics shown in parentheses ***, **, and * denote significance at the 1 %, 5 %, and 10 % levels; L, L2, and L3 represent one-period lag, two-period lag, and three-period lag; AR(1), AR(2), and Hansen are reported for a p-value.

Table 5
Transmission channels tests of the smart city on green innovation.

VARIABLES	(1)	(2)	(3)	(4)	(5)	(6)
	abstaul	gpatent	vcpe	gpatent	newfirm	gpatent
smartcity	−0.0924***	0.0986***	2.5176**	0.1001***	1.1083***	0.0986***
	(-2.8584)	(3.1299)	(2.3493)	(3.1694)	(2.6933)	(3.1299)
abstaul		−0.0317**				
		(-2.0285)				
vcpe				0.0010**		
				(2.0811)		
newfirm						0.0068***
						(5.5688)
Control variables	YES	YES	YES	YES	YES	YES
Time fixed	YES	YES	YES	YES	YES	YES
City fixed	YES	YES	YES	YES	YES	YES
Observations	4178	4178	4163	4163	4163	4163
R-squared	0.099	0.814	0.005	0.814	0.068	0.815

Note: The t-statistics shown in parentheses ***, **, and * denote significance at the 1 %, 5 %, and 10 % levels.

geographical location, and level of marketization are further discussed.

4.5.1. Population size heterogeneity

Cities were divided into two subsamples with the median of the average population size over the sample period, and the estimation results are shown in columns (1) and (2) of Table 6. The positive impact of smart city construction on green innovation is significant only in cities with larger population sizes. The possible reasons for this result are twofold. First, compared with cities with smaller populations, affluent labor resources in large cities can provide adequate factor support for the development of green innovation and broad space for smart city construction to release the dividends of optimizing factor allocation. This provision significantly promotes the development of green innovation. Second, cities with larger population sizes have promising market prospects, which can be more attractive to the entry of venture capital and enterprises. The construction of smart cities will amplify this advantage in promoting green innovation.

4.5.2. City administrative rank heterogeneity

The cities were divided into two subsamples of provincial capitals and general prefecture-level cities according to the administrative rank, and the estimation results are shown separately in columns (3) and (4) of Table 6. Smart city construction only significantly positively affects green innovation in general prefecture-level cities. This result is probably due to that provincial capitals enjoy a political tilt of resources, especially supported by a strategy to strength provincial capitals, and their green innovation has already been well developed before the implementation of the policy (the difference between group means is significant at a 1 % significance level) such that the gainful effect of smart city construction is limited. By contrast, optimization in general prefecture-level cities has more room for improvement, and smart city construction can support green innovation by optimizing the allocation of resources and attracting venture capital and enterprises in these cities.

4.5.3. Geographic location heterogeneity

The sample was divided into two parts along the boundary line of "The Qinling–Huai River," and the results are shown in the first two columns of Table 7. Smart city construction significantly impacts green innovation in the southern cities but not in the northern cities. Regarding the differences between the two subsamples, the study by Ruan et al. [63] provided supporting evidence that the culture in the south is more focused on cooperation and collectivism, which are capable of stimulating creativity and innovation [64], compared with the northern regions. The construction of smart cities produces an amplification mechanism for this culture of cooperation by strengthening the communication and exchange of information among inventors. Thus, it shows an outstanding

Table 6
Heterogeneity analysis estimation in city size and city administrative rank.

VARIABLES	Population size		City administrative rank	
	small	large	capital	general
smartcity	−0.0464	0.1858***	−0.0853	0.1127***
	(-0.9349)	(4.6561)	(-1.2939)	(3.2814)
Control variables	YES	YES	YES	YES
Time fixed	YES	YES	YES	YES
City fixed	YES	YES	YES	YES
Observations	2069	2109	374	3804
R-squared	0.767	0.862	0.951	0.803

Note: The t-statistics shown in parentheses ***, **, and * denote significance at the 1 %, 5 %, and 10 % levels.

promotion effect on green innovation in southern cities.

4.5.4. Marketization level heterogeneity

The cities were divided into two subsamples based on the median of the marketization index (compiled in China Marketization Index Report), and the results are shown in the last two columns of Table 7. Smart city construction only significantly promotes green innovation development in cities with high marketization levels. Concerning the difference between the subsamples, institutional theory suggests that imperfect market mechanisms can cause problems such as weak awareness of property rights protection and nontransparent systems, which increase market transaction costs and inhibit the willingness to innovate. At the same time, higher marketization is conducive to the green innovation effect of smart city construction by creating a good business environment and reducing market transaction costs [65].

4.6. Industrial emission reduction effect of smart city and green innovation

The results of the previous analysis have shown that smart city construction helps play a role in promoting green innovation. However, whether it substantially improves green development is still unknown, and the role of green innovation in this effect is unclear. Further analysis of the industrial emission reduction effect of smart city construction and green innovation was conducted to form a complete analytical framework. The interaction term between smart city policy and green innovation (*smartcity_gpatent*) was added in the regression analysis to explore their joint effects on industrial emission. Industrial SO_2 and wastewater emissions were selected as the dependent variables, and low-carbon policy (*lowcarbon*) was controlled for more reliable conclusions.

Estimation results are presented in Table 8, where smart city construction and green innovation were shown to generate significant collaboration and jointly reduce industrial emissions. This point coincides with those previously held by Luo et al. [6] and provides a good reform idea for industrial emission reduction, with smart city construction and green innovation being key focus points in promoting green development. At the same time, considering that technological development is the result and source of intelligence and digitalization [66], it is necessary to form a virtuous circle between smart city construction and green innovation and jointly exert the synergistic effect of the two concepts on green development.

In addition, the insignificant effect of green innovation on SO_2 emissions (columns (1) and (2)) implies that green innovation does not affect SO_2 emissions other than its synergistic effect with the construction of smart cities. In other words, the achievement of its emission reduction target must be combined with smart city construction. Nevertheless, the coefficients of *gpatent* in columns (3) and (4) are significant at a 5 % significance level, which suggests that green innovation plays an essential and superior role in wastewater emissions.

5. Conclusions and implications

5.1. Conclusions

Green development is an eternal theme of global development, and urban system management, as a carrier of economic and environmental construction, is crucial to building a green and sustainable environment. Taking China's smart city pilot policy as a quasi-natural experiment, this study uses a multi-temporal difference-in-difference method and city panel data to analyze the impact, mechanism channels, and heterogeneity characteristics of smart city construction on green innovation. Furthermore, the joint effect of the two constructs on industrial emissions is discussed. These analyses provide a new way of promoting green innovation, reducing industrial emissions, and realizing green development and ecological construction.

The main conclusions drawn in this study are as follows. First, smart city construction has a significant positive impact on the development of green innovation, with an impact coefficient of 0.1015. However, this role will be weakened in the long run by the failure to substantially improve innovation capacity and innovation-free-riding behaviors. Thus, the intensity of smart city construction on green innovation shows an inverted U-shaped trend of first rising and then falling. In addition, the prior research base plays a vital role in the development of green innovation, with a coefficient of 0.4815 for the one-period lag term and a coefficient of 0.1394 for the two-period lag term. Second, smart city construction not only has a direct positive impact on green innovation but also exerts an indirect positive impact on green innovation through such channels as correcting distortions in the allocation of labor factors, attracting venture capital, and enhancing market accessibility. Third, the impact of smart city construction on green innovation is characterized by apparent heterogeneity. In other words, smart city construction shows positive impacts only in cities with larger population sizes, general prefecture-level cities, southern cities, and cities with higher levels of marketization, but not in other cities. Fourth, the construction of smart cities and green innovation jointly have an inhibitory effect on industrial SO_2 emissions and wastewater emissions, with coefficients of -0.0246 and -400.6034, respectively. Green innovations also negatively affect industrial wastewater emissions, with a coefficient of -267.1948. Thess effects remain significant after excluding the low-carbon policy, which confirms the positive significance of smart city construction and green innovation on green development.

5.2. Implications

The findings of this study provide some insights to promote the development of the green economy. First, despite some shortcomings in the current scheme of smart city construction [23,67], various studies have nevertheless recognized its role in green development [14,16,17], which should therefore not be ignored. A localized and orderly promotion of smart cities would greatly

Table 7
Heterogeneity analysis estimation in geographic location and marketization level.

VARIABLES	Geographic location		Marketization level	
	southern	northern	low	high
smartcity	0.1155***	0.0622	0.0085	0.2571***
	(2.7718)	(1.4049)	(0.1727)	(5.8415)
Control variables	YES	YES	YES	YES
Time fixed	YES	YES	YES	YES
City fixed	YES	YES	YES	YES
Observations	2270	1908	2085	2093
R-squared	0.862	0.767	0.717	0.874

Note: The t-statistics shown in parentheses ***, **, and * denote significance at the 1 %, 5 %, and 10 % levels.

Table 8
Industrial emission reduction effect of smart city and green innovation.

VARIABLES	(1)	(2)	(3)	(4)
	so2	so2	wastewater	wastewater
smartcity_gpatent	−0.0228***	−0.0246***	−402.0001***	−400.6034***
	(-4.0807)	(-4.3843)	(-8.6936)	(-8.6213)
gpatent	0.0022	0.0058	−264.4545**	−267.1948**
	(0.1439)	(0.3731)	(-2.0423)	(-2.0584)
lowcarbon		0.1030***		−80.2648
		(3.2869)		(-0.3091)
Control variables	YES	YES	YES	YES
Time fixed	YES	YES	YES	YES
City fixed	YES	YES	YES	YES
Observations	3930	3930	3931	3931
R-squared	0.608	0.609	0.136	0.136

Note: The t-statistics shown in parentheses ***, **, and * denote significance at the 1 %, 5 %, and 10 % levels.

benefit cities in the long run. The construction of smart cities should be continuously and steadily promoted, the scope of smart city construction should be broadened, and the digital infrastructure should be improved to strengthen the joint flow of information and knowledge within and among cities. These initiatives can further promote the positive impact of smart city construction in correcting distortions in the allocation of factors, strengthening the attraction of venture capital and firms, and reducing industrial emissions.

Second, differentiated smart city construction policies and green innovation strategies should be formulated for cities with different characters. For cities with a better foundation for innovation, such as provincial capitals and cities with larger population sizes, the role of cooperation and marketization construction in promoting green innovation can be further emphasized [64,65]. On the one hand, this emphasis can be achieved through creating a favorable business environment, promoting the optimal allocation of local innovation resources and the attraction of external resources, and strengthening the accumulation and efficient utilization of innovation factors; on the other hand, it can be done through utilizing encouraging cooperation, strengthening the sharing of innovation costs and knowledge sharing, and providing more opportunities for knowledge recombination. For cities with a weak foundation for green innovation development, the key lies in upgrading R&D capabilities. Such upgrading can be supported by increasing financial support and guiding the formation of innovation cooperation among cities with various advantages in innovation.

Third, industrial emission reduction is a long-term endeavor. Therefore, this cost can be internalized to the enterprise in the form of a tax, and green demand can be simulated to promote the use of green technologies [68]. Multiple policies can also be applied simultaneously [5,69]. Implementing relevant policies should also avoid conflicting priorities between different government levels, which would weaken government intervention policies and their intended effects.

5.3. Limitations and future research directions

This study represents only a small fraction of the extensive research on the effects of green innovation and industrial emissions reduction in cities. Future research can determine the nonlinear impact of smart city construction on green innovation by relying on channels such as information network construction and its emission reduction effect, as well as the transmission mechanism among the three constructs from the level of industry–academia–research collaboration.

Data availability statement

The data associated with the study has not been deposited into a publicly available repository. The data presented in this study are available on request from the corresponding author.

CRediT authorship contribution statement

Qianqian Sun: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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