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*Original Research*

# Does Digital Infrastructure Construction Serve as a New Engine for Green Sustainable Innovation? A Quasi-Natural Experiment Based on the "Broadband China" Pilot Policy

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## Abstract

The broadband network is driving a new wave of informationization development, and many countries have prioritized broadband network development as a strategic area of action. It is also seen as an important initiative to gain a competitive edge in international economic, scientific, technological, and industrial competition in the new era. Digital infrastructure development, as a crucial driver of modernization, plays a pivotal role in fostering green and sustainable innovation. This study employs a quasi-natural experimental approach based on "Broadband China" pilot cities, using a difference-in-differences (DID) model to explore the impact of digital infrastructure development on green and sustainable innovation in Chinese prefecture-level cities. Research results manifest that the construction of "Broadband China" significantly promotes green sustainable innovation. The capital deepening effect brought by large-scale investment and the popularization of high-speed broadband networks greatly improves information access and dissemination efficiency, optimizes resource allocation, reduces energy waste, and promotes the R&D and application of green technology. Heterogeneity analysis reveals that cities with a medium level of openness to the outside world benefit more significantly from the "Broadband China" policy. From the perspective of resource-dependent cities, the policy significantly promotes green and sustainable innovation in mature and non-resource-dependent cities. Mechanism analysis indicates that "Broadband China" fosters green and sustainable innovation through enhanced digitalization and improved energy efficiency, while unemployment rates negatively moderate the relationship between "Broadband China" and green sustainable innovation.

**Keywords:** green sustainable innovation, broadband China, difference-in-differences model, digital transformation

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## Introduction

Environmental problems are becoming increasingly severe globally, with climate change, resource depletion, and environmental pollution posing significant challenges to human survival and development [1]. According to the United Nations Framework Convention on Climate Change (UNFCCC) report, the global average temperature has already risen by 1.1°C above pre-industrial levels, and without effective measures, the global temperature is projected to rise to between 2.5°C and 4.5°C by the end of this century. Additionally, global resource consumption reached 100 billion tons in 2019, while the resource recovery rate was only 8.6%, indicating that humanity's utilization of natural resources is alarmingly low, highlighting serious technological shortcomings and the urgent need for innovation to improve resource utilization efficiency. In response to these environmental challenges, countries worldwide have adopted strategic goals for green and sustainable development. The European Union has introduced the "European Green Deal," which aims to reduce carbon emissions and resource wastage by improving energy efficiency, developing renewable energy, promoting sustainable agriculture and the circular economy, and achieving carbon neutrality by 2050. The United States has recommitted to the Paris Agreement, with a goal to reduce greenhouse gas emissions by 2030 to half of the 2005 levels by promoting clean energy, upgrading fuel efficiency, introducing stringent emission reduction policies, supporting green technological innovations, and protecting and restoring natural resources. Japan has set a strategic goal of achieving carbon neutrality by 2050, focusing on the development of renewable energy and hydrogen technology, promoting environmentally friendly transportation, enhancing building energy efficiency, and implementing a circular economy to reduce waste generation and resource wastage. Similarly, Germany aims to achieve carbon neutrality by 2050 through its energy transition policy, vigorously developing renewable energy sources such as wind and solar energy, enhancing energy efficiency, advancing electric transportation and energy storage technologies, and promoting corporate emissions reduction through the carbon emissions trading system. Overall, developed countries and regions are widely applying green innovative technologies in their pursuit of green sustainable development. Through policy guidance and technological progress, they have achieved multiple goals, including optimizing energy structures, improving resource efficiency, and enhancing environmental protection.

While developed countries have made remarkable progress toward green and sustainable development, developing countries are also actively exploring paths toward green development. Especially in the face of environmental challenges and resource scarcity, the experiences and practices of developing countries are of great significance to global environmental governance. As the world's second-largest economy, China faces serious environmental challenges. China's carbon emissions account for 35.8% of the global total (e.g., Fig. 1), making it the world's largest carbon emitter. At the same time, China's resource consumption is growing rapidly, reaching 5.72 billion tons in 2023. To address these challenges, the Chinese government has clearly stated in the 14th Five-Year Plan that it will achieve the goal of carbon peaking by 2030 and carbon neutrality by 2060. This ambitious goal requires China to make greater efforts in green innovation and to promote technological advances and institutional innovations to ensure that the goal of carbon neutrality will be achieved within the set time frame. According to the Outline of the National Innovation-driven Development Strategy, China will invest more than 1.5 trillion yuan in green technology research and development and promotion over the next decade. Meanwhile, China is also promoting the development of green industries and the application of green technologies through policy

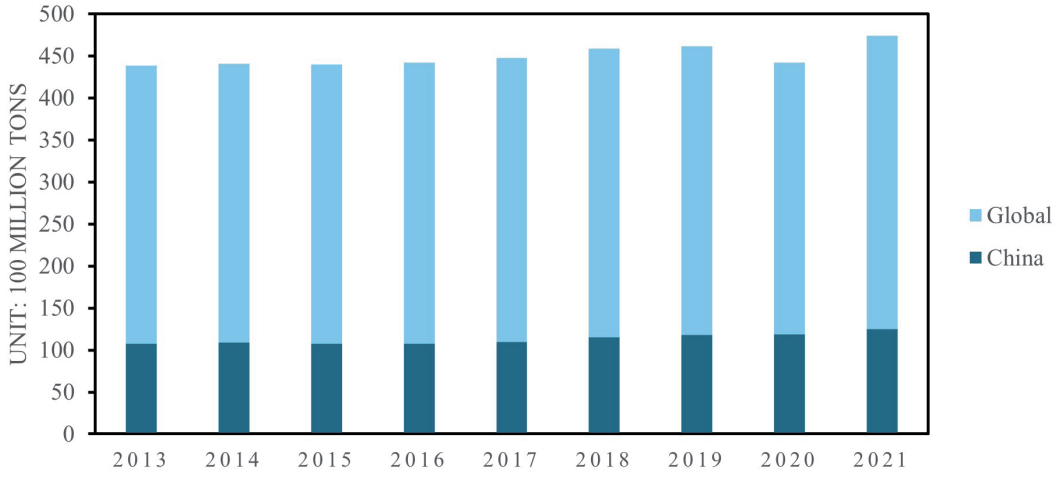


Fig. 1. Total global and Chinese carbon emissions.

incentives, financial support, and market mechanisms [2].

However, despite its many efforts in green sustainable innovation, China still faces problems such as irrational resource allocation, immature technologies, and weak policy implementation [3, 4]. These problems limit the application and diffusion of green technologies. Solving them will help reduce greenhouse gas emissions and slow down global warming; improve the efficiency of resource utilization and reduce the waste of resources; and promote the development of green industries and the realization of sustainable economic growth [5, 6]. This can improve the environmental and economic conditions of developing countries and play a positive role in promoting global environmental governance. In the process of realizing green development, these countries can also explore green technologies and policies suitable for their own development, contributing to global green sustainable innovation.

Digital infrastructure and low-carbon development are both essential for sustainable growth. By harnessing the potential of digital innovation, we can effectively promote the sustainable development of a green economy [7]. The Chinese government launched the "Broadband China" strategy in 2013, aiming to accelerate the construction of information infrastructure and improve network coverage and speed. The spread of broadband networks can significantly enhance the efficiency of information access and dissemination, optimize resource allocation, and reduce energy waste [8]. Additionally, the application of broadband technology enables enterprises to use big data and IoT technology to manage resources and optimize production processes more accurately, thereby promoting the research, development, and application of green technologies [9]. The building of digital infrastructure is crucial for green sustainable innovation as it provides the necessary technical support and platforms that enable green technologies and innovations to be sustainably and effectively implemented and scaled up. Exploring the impact of the "Broadband China" policy on green and sustainable innovation can reveal whether digital infrastructure development can play a role in promoting a green economy and sustainable development, and whether it can help China achieve the goals of carbon peaking and carbon neutrality, setting an example for developing countries.

This paper focuses on the Chinese context not only because of its importance in global carbon emissions and resource consumption but also because of the Chinese government's proactive policies and large-scale investments in promoting green technological innovation and sustainable development [10]. According to the China Broadband White Paper, the "Broadband China" strategy elevates broadband facilities to the status of strategic national public infrastructure for the first time, helping to build and improve broadband infrastructure in all regions. Using the "Broadband China" pilot policy as an entry point to study China's green innovation policies and practices can provide other countries with experience in promoting green technology development under policy incentives and market mechanisms to facilitate economic transformation and sustainable growth.

The possible marginal contributions of this paper are:

(1) The theory of sustainable innovation posits that continual changes in the external environment compel firms to leverage organizational sustainable innovation for optimal alignment. In contrast to established studies, this research emphasizes the dynamic effects of innovation, particularly by introducing the concept of green sustainable innovation. We construct a quasi-natural experiment stemming from the implementation of the Broadband China pilot policy to investigate the impact of digital infrastructure development on green sustainable innovation. This approach not only expands the research boundaries of green innovation but also charts a new pathway for green sustainable development, thereby enhancing the theoretical framework of green innovation.

(2) This paper tests the impact mechanism of "Broadband China" on green sustainable innovation based on two perspectives: digital transformation and energy efficiency improvement. Additionally, this paper examines the moderating effect of human capital on the relationship between "Broadband China" and green sustainable innovation. This not only enriches the literature on the impact of digitalization policies on green innovation but also provides insights for promoting green, high-quality development in future work.

(3) Based on the differences in city characteristics, the heterogeneous effects of differences in openness level and resource endowment are carefully analyzed, thus giving sufficient data and theoretical support for the implementation of the digital transformation strategy and the enhancement of green sustainable innovation capacity, as well as providing insights for government departments to implement policies more precisely.

## Theoretical Analysis and Research Hypotheses

Advancements in digital infrastructure have enhanced environmental information disclosure and reduced uncertainty, facilitating the widespread adoption of green technologies [11]. By improving connectivity, the implementation of the "Broadband China" strategy reduces barriers to information flow and makes the matching between resources and demand more efficient. Digital governance theory suggests that digitization can be applied to existing governance systems as a tool or instrument to effectively improve governance effectiveness. The optimization of resource allocation can be explained by the theory of economic externalities, in which digital platforms facilitate the efficient functioning of markets by reducing information

asymmetry and transaction costs [12]. For example, digital platforms facilitate the integration of supply chains, optimize resource scheduling and allocation through real-time data and analytics, and improve overall productivity [13]. Additionally, the implementation of the "Broadband China" strategy has significantly driven investment in green technology R&D, a process that potentially facilitates technological innovation. The widespread use of big data and advanced analytics tools has enabled firms to conduct more efficient and targeted R&D activities, leading to green technology breakthroughs.

Research has shown that cities with better digital infrastructure experience significant improvements in green innovation capabilities, especially in green innovation areas involving substantial technological advances [14]. This suggests that the implementation of the "Broadband China" strategy not only improves the technological innovation capability of enterprises but also promotes the green transformation of the whole industry through knowledge spillover effects [15]. Additionally, the implementation of the "Broadband China" strategy further promotes the level of green innovation by opening up to the outside world and promoting the upgrading of industrial structure [16]. For example, the rapid development of information and communication technology (ICT) has changed the way people work, learn, and communicate, and constructed a clean and smart industrial chain through technological innovation, promoting green innovation [17]. Furthermore, the penetration of digital technology has improved the decision-making efficiency of enterprises and promoted a greener development path [18]. Summarizing the above analysis, the implementation of the "Broadband China" strategy promotes green technology innovation and application through multiple pathways, thus promoting green and sustainable innovation. Therefore, we propose the following hypotheses:

H1: The "Broadband China" pilot policy can promote green sustainable innovation.

There are differences in the effects of the "Broadband China" pilot policy on the promotion of green sustainable innovation capacity in cities with different levels of openness to the outside world. The degree of openness of a city affects the introduction of external resources and technologies and determines the city's position and role in the global innovation network. According to the theory of comparative advantage, cities with high levels of openness to the outside world can quickly access advanced global technologies and resources, but they also face higher competitive pressures and uncertainty in the external environment, which affects the effectiveness of policy implementation [19]. According to the theory of capital accumulation, cities with lower degrees of openness to the outside world find it challenging to make large-scale digital infrastructure investments and technology introductions due to insufficient capital accumulation. Due to weak infrastructure, it is difficult to fully capitalize on the innovation opportunities arising from digital infrastructure development [20]. In contrast, cities with a medium level of openness to the outside world can introduce the necessary external resources and technologies, digest and absorb them in a relatively stable environment, and transform them into their own innovation capabilities, thus effectively contributing to resource efficiency and environmental sustainability. Based on the above analysis, the following hypotheses are proposed:

H2A: The "Broadband China" pilot policy significantly promotes green and sustainable innovation capacity in medium-level open cities.

There may be significant differences in the effectiveness of the policy implementation among different types of cities [21]. According to the diffusion of innovation theory, the diffusion of innovations is highly dependent on the degree of infrastructure sophistication and the level of economic development. Mature cities can absorb and apply new technologies more quickly due to their well-developed infrastructures and higher economic levels, which makes these cities more effective in promoting green innovation when implementing the "Broadband China" pilot policy. Nie et al. [22] suggest that the development of information infrastructure has a significant effect on urban green innovation, particularly in large, high-grade cities with high levels of economic development. This is because these cities have better resource allocation, higher innovation capacity, and greater ability to leverage technological progress and resource advantages brought about by policies. Non-resource-based cities, on the other hand, need to rely on external resources and improve resource utilization efficiency and environmental sustainability through technological innovation. According to the resource dependence theory, non-resource cities must rely on external resources and technologies to promote their own development due to their limited resources. Liu et al.'s [23] study shows that these cities optimize resource allocation and improve environmental management through the introduction and application of new technologies, thus significantly promoting the application of green technologies. On this basis, the following hypotheses are proposed:

H2B: The "Broadband China" pilot policy significantly promotes green and sustainable innovation in mature and non-resource cities.

Digital transformation plays an important role in promoting green and sustainable innovation in cities. According to the urban innovation system theory, the innovation capacity of a city as an integrated entity depends not only on the optimization of internal resources and technologies but also on its systemic changes in the digitalization process. Through the "Broadband China" pilot policy, cities can significantly improve their digital infrastructure, achieve efficient data management, and optimize the allocation of resources. The application of Internet of Things (IoT) and big data analytics can help cities achieve real-time

monitoring and management of transportation, energy, and the environment, thereby optimizing resource use, reducing pollution emissions, and improving operational efficiency [24]. Additionally, the regional spillover effect brought about by digital transformation is a factor that cannot be ignored at the city level. Through the cross-regional dissemination of information and technology, the digital innovation experience and technological achievements of advanced cities can diffuse to the surrounding areas, leading to green technology innovation and sustainable development in the whole region. On this basis, the following hypotheses are proposed:

H3A: The "Broadband China" pilot policy promotes green and sustainable innovation by accelerating digital transformation.

Through technological innovation and institutional change, modern societies can achieve a balance between economic growth and environmental protection [25]. Improving energy efficiency is one of the key ways to achieve this goal. The "Broadband China" pilot policy promotes the development and application of green technologies by optimizing energy management and improving efficiency in cities, which significantly reduces resource wastage and pollution emissions. Li [26] points out that the development of digital infrastructure significantly improves the efficiency of energy use, reduces resource wastage and pollution emissions, and thus promotes green technological innovation. Ghimire [27] also shows that improving energy efficiency not only helps to reduce carbon emissions but also enhances the sustainability of cities. Therefore, based on the theory of ecological modernization, we propose the following hypothesis:

H3B: The "Broadband China" pilot policy promotes green and sustainable innovation through energy efficiency.

The theory of effective demand suggests that a rise in unemployment leads to a decrease in aggregate demand, which affects economic growth and willingness to invest. When unemployment is high, consumer spending decreases, and firms' profitability declines, leading to reduced investment in new and green technologies, which can weaken the role of policies in promoting green and sustainable innovation. The impact of unemployment on green innovation is complex, necessitating a balance between economic development and environmental protection [28-30]. Policymakers need to consider how to promote employment without hindering the implementation and promotion of green innovation and environmental protection. Based on the above analysis, we propose the following hypothesis:

H3C: The promotion effect of the "Broadband China" pilot policy on green and sustainable innovation will weaken as the unemployment rate rises.

Research framework is shown in Fig. 2.

## Material and Methods

### Variable Selection

#### *Explained Variables*

The explanatory variable in this paper is green and sustainable innovation *(Growth)*. The growth in the number of patents reflects the "sustainability" of green innovation activities and competitiveness in the field of green technologies, providing information on

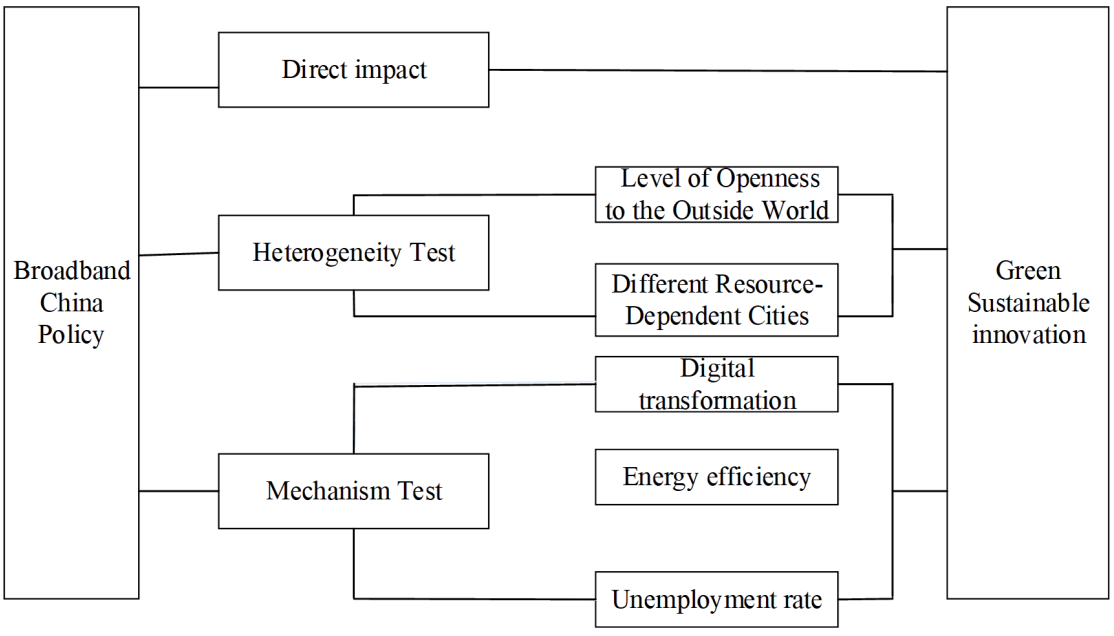


Fig. 2. Research framework.

technological trends that is useful for assessing the actual impact and success of green and sustainable innovation. We measure *Growth* using the following equation (1):

$$\text{Growth} = \frac{P_{t+1} - P_t}{P_t} \quad (1)$$

where P represents the number of green patents obtained and t represents the starting year.

*Explanatory Variables*

The core explanatory variable in this paper is the "Broadband China" pilot city policy (kdzg). We use dummy variables to assign values: if a city in the sample belongs to the pilot city after the start of the pilot, it is assigned a value of 1; otherwise, it is assigned a value of 0.

*Control Variables*

This paper refers to the research methods of Omri [31], Wei et al [32], and Zhu et al [33], and selects the following control variables:

(1) Population size (lnpop): Measured by the city's household population.

(2) Economic development (lnGdpp): Measured by the per capita gross domestic product.

(3) Science and technology investment (lnkxjs): Measured by the city's science and technology expenditure.

(4) Environmental regulation intensity (lnmswhr and $lnso_2$): Measured using the city's domestic waste disposal rate and the city's industrial sulfur dioxide emissions (tons).

(5) Financial development (lnhhd): Measured by the household deposit balance in ten thousand yuan citywide.

*Mechanism Variables*

To verify hypotheses H3A and H3B, this paper explores the mechanism of "Broadband China" affecting green sustainable innovation from two dimensions: the degree of digitalization and energy substitution.

(1) Level of digitization: Drawing on Bai's study [34], this paper uses the number of word frequencies of the digital economy to measure the degree of urban digitization.

(2) Energy substitution: Drawing on Hong's study [35], this paper uses the total supply of artificial gas and natural gas to measure the transformation of the energy structure, reflecting differences in the use of energy beyond traditional energy sources.

*Moderating Variable: Human Capital*

Human capital is the moderating variable in this study. The number of unemployed persons can reflect the tightness of the labor market and the efficiency of human resource utilization. In this paper, the number of registered unemployed people in the city is chosen to measure the level of human capital in the city.

## Model Design

On August 1, 2013, the State Council formulated and issued the "Broadband China" strategy and implementation plan, aiming to develop broadband networks, pull effective investment, promote information consumption, and support the transformation of development modes and the construction of a well-off society. "Broadband China" is characterized by "early and pilot implementation," meeting the conditions of a quasi-natural experiment. The exogenous nature of the policy choices ensures that the implementation is not related to the innovation level of the region itself.

The DID approach analyzes the net impact of a policy by treating its implementation as a natural experiment. It compares an experimental group affected by the policy with a control group that is unaffected [36]. To accurately identify the causal relationship between the construction of "Broadband China" and green and sustainable innovation, a multi-period DID model is constructed as follows:

$$Y_{it} = \beta_0 + \beta_1 kdzg + \alpha Controlit_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (2)$$

where $Y_{it}$ is the explanatory variable, expressed as the number of green patents obtained in this paper, kdzg is the core explanatory variable of "Broadband China" in this paper, $Control_{it}$ denotes a series of control variables affecting green sustainable development, $\gamma_t$ denotes the time fixed effect, $\mu_i$ denotes the city fixed effect, $\varepsilon_{it}$ denotes the random error term, i denotes the city, and t denotes the year.

Further, to explore the mechanism by which the construction of "Broadband China" affects green sustainable innovation, a mechanism test is needed. Most existing studies adopt the following mechanism testing model:

$$\text{Growth} = \beta_0 + \beta_1 kdzg + \alpha\, Control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (3)$$

$$m = \Phi_0 + \Phi_1 kdzg + \Phi\, Control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (4)$$

$$Growth = \eta_0 + \eta_1 kdzg + \eta_2 m + \eta Control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (5)$$

where m is the mediating variable and $\beta_0$, $\varphi_0$ and $\eta_0$ are the intercept terms. If all three conditions are satisfied: (1) testing the relationship between the independent and dependent variables; (2) testing the relationship between the independent variable and the mediating variable; and (3) testing the relationship between the mediating variable and the dependent variable, it indicates that the mechanism of m as a channel of action is valid.

According to the conclusion of Fan et al. [37], the study should focus on improving the causal relationship of the explanatory variables to the explained variables, use the same method to identify the causal relationship of the explained variables to the mediating variables, and try to avoid proposing mediating variables that do not have an obvious causal relationship with the explained variables. Therefore, this paper will focus on analyzing the causality of (3) and (4) and replace (5) with theoretical analysis.

To verify the moderating effect model, this paper constructs the following moderating effect model:

$$Growth = \sigma_0 + \sigma_1 kdzg + \sigma_2 (lnup \times kdzg) + \sigma Control_{it} + \gamma_t + \mu_i + \varepsilon_{it} \quad (6)$$

where lnup denotes the level of human capital.

### Data Sources

Since the outbreak of the international financial crisis, the global economy, especially the traditional financial industry, has been severely hit. Countries have formulated digital economy strategies, hoping to promote economic recovery through the development of the digital economy. Therefore, the sample starting time of this paper is 2008. Given data availability, this paper chooses 282 cities nationwide as the sample, with data up to 2021. For the missing values in the sample, we use linear interpolation to fill in. To unify the data dimensions, the non-dummy variables were processed with logarithmic transformation. The data are obtained from the China Statistical Yearbook, China Urban Statistical Yearbook, and CSMAR database. The descriptive statistics of the data are shown in Table 1.

## Results and Discussion

### Baseline Regression Analysis

Table 2 reports the estimation results of the impact of the construction of "Broadband China" on green sustainable innovation. Columns (1), (2), (3), and (4) present the regression results under different control conditions: both time and individual fixed effects (1), time fixed effects only (2), individual fixed effects only (3), and without any fixed effects (4). Notably, when controlling for the year and city fixed effects, the coefficient for "Broadband China" construction is 0.1557, which is statistically significant at the 5% level. This finding indicates that the "Broadband China" initiative is associated with an increase of 0.156 units in green sustainable innovation.

This may be because the implementation of "Broadband China" leads to a capital deepening effect. Large-scale investment and the popularization of high-speed broadband networks significantly improve the efficiency of information access and dissemination, optimize resource allocation, reduce energy waste, and promote the research, development, and application of green technology. Additionally, the application of broadband networks has enabled enterprises to manage resources and optimize production more accurately

Table 1. Descriptive Statistics.

| Variable | Obs | Mean | Std. dev. | Min | Max |
|---|---|---|---|---|---|
| Growth | 3792 | 0.365 | 0.821 | -1.792 | 4.500 |
| kdzg | 3792 | 0.192 | 0.394 | 0.000 | 1.000 |
| lnGdpp | 3792 | 10.869 | 0.594 | 9.316 | 12.076 |
| lnhhd | 3792 | 16.196 | 0.991 | 14.055 | 18.891 |
| lnpop | 3792 | 5.892 | 0.668 | 3.844 | 7.217 |
| lnso2 | 3792 | 10.232 | 1.503 | 6.219 | 13.447 |
| lnmswhr | 3792 | 4.481 | 0.273 | 3.039 | 4.605 |
| lnkxjs | 3792 | 10.248 | 1.431 | 7.492 | 14.412 |
| szii | 3792 | 5.537 | 7.414 | 0.000 | 98.000 |
| lnrgmq | 3792 | 8.830 | 2.081 | 0.000 | 14.497 |
| lnup | 3792 | 9.813 | 0.813 | 4.961 | 16.750 |

Table 2. Results of the Impact of "Broadband China" Construction on Green Sustainable Innovation.

| Variables | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| kdzg | 0.1557** | -0.03 | 0.0815 | -0.0418 |
| | (2.25) | (-0.66) | (-1.30) | (-0.66) |
| lnGdpp | 0.0062 | -0.0853* | 0.0045 | -0.0746 |
| | (0.08) | (-1.87) | (-0.05) | (-1.46) |
| lnhhd | 0.0521 | -0.0900** | -0.0008 | -0.0638 |
| | (0.54) | (-2.17) | (-0.01) | (-1.34) |
| lnpop | -0.5935 | -0.0514 | -0.5946 | -0.0612 |
| | (-1.36) | (-0.93) | (-1.37) | (-1.21) |
| lnso2 | 0.0209 | 0.002 | -0.0087 | -0.0162 |
| | (0.61) | (0.10) | (-0.54) | (-1.11) |
| lnmswhr | 0.1769* | 0.1542 | 0.1724* | 0.1680** |
| | (1.70) | (1.58) | (1.67) | (2.29) |
| lnkxjs | -0.08 | 0.0032 | -0.0843 | -0.0031 |
| | (-1.12) | (0.11) | (-1.19) | (-0.11) |
| Constant | 2.6388 | 2.0890*** | 4.0307* | 2.0546*** |
| | (0.85) | (2.79) | (1.85) | (3.38) |
| Year Fe | Controlled | Controlled | Uncontrolled | Uncontrolled |
| City Fe | Controlled | Uncontrolled | Controlled | Uncontrolled |
| N | 3792 | 3792 | 3792 | 3792 |
| $R^2$ | 0.0335 | 0.0305 | 0.0033 | 0.0012 |

Note: * p<0.1, ** p<0.05, *** p<0.01, t statistics in parentheses.

through big data and IoT technologies. This not only improves labor productivity in the microeconomic sector but also further provides important support for green and sustainable innovation, empowering the green transformation and sustainable development of the economy. This result validates the theory of sustainable development, which asserts that digital transformation fulfills human needs while promoting environmental sustainability.

## Parallel Trend Test

The basic premise of the policy test using the multi-period double-difference method is that the green innovation level of the "test group" and the "control group" before the policy implementation maintains a consistent trend. We use the event study method to test for parallel trends, using the difference between the current point in time and the policy implementation node (current) to determine the early and late stages of policy implementation, with 0 being the period when the pilot policy was implemented. We use data from the four years before the policy implementation to the second year after its implementation for the parallel trend test. The test results are shown in Fig. 3. We find that in the four years prior to the policy implementation, the coefficients are not significant or significantly negative, fluctuating around 0, indicating that the experimental group and the control group had no significant difference in green innovation levels before the implementation of the "Broadband China" pilot policy. After the implementation of the "Broadband China" policy, the difference in the level of green sustainable innovation between the experimental group and the control group is significantly different from 0. This indicates that the effect of the "Broadband China" construction on green sustainable innovation has a certain degree of continuity and stability, passing the parallel trend test. Dynamic policy effects will become significant within the first year of implementation.

## Robustness Check

### *Placebo Test*

To further exclude the influence of other unknown factors on green sustainable innovation in the pilot cities of "Broadband China" and to ensure that the level of

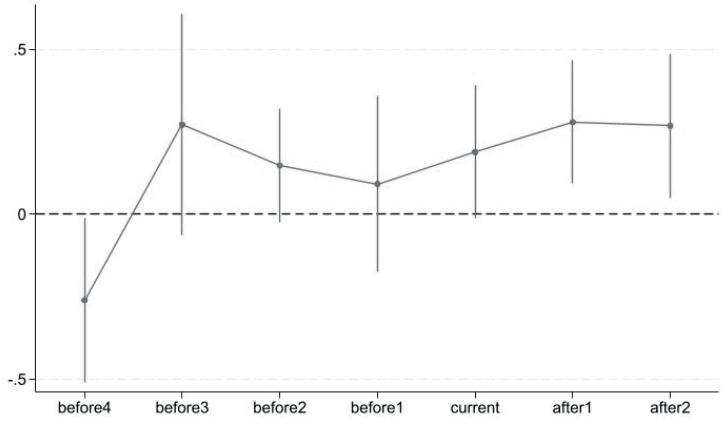


Fig. 3. Parallel trend test.

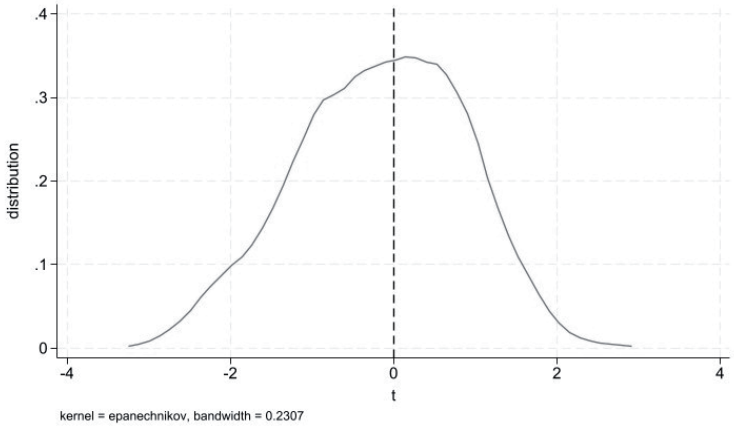


Fig. 4. Placebo test.

green sustainable innovation in the experimental group is controlled by the "Broadband China" policy, this paper conducts a placebo test. The placebo test is conducted by randomly assigning pilot cities and randomly selecting the time when the "Broadband China" policy was implemented, and the entire regression process is repeated 1000 times. If the regression coefficients of random variables are normally distributed around 0 during the random sampling process, it indicates that the explanatory variables do not have a significant effect on green sustainable innovation, confirming the robustness of the regression results in this paper. The results of the placebo test are shown in Fig. 4. The figure demonstrates that the t-values of the random variables are normally distributed around 0, indicating that the impact of the "Broadband China" policy on green sustainable innovation in the pilot cities has not been influenced by unknown factors. Therefore, our regression results are robust.

*Excluding the Influence of Other Policies*

To avoid the interference of other policies on the regression results during the sample period, this paper introduces the dummy variable of the "Big Data Comprehensive Experimental Zone" pilot policy into the model and regresses it again. The regression results are shown in column (1) of Table 3. It is found that, after considering the impact of the pilot policy of the "Big Data Comprehensive Experimental Zone," the policy coefficient of the "Broadband China" policy is still significantly positive at the 10% level, indicating that the regression results are not interfered with by the policy of the Big Data Comprehensive Experimental Zone, and the regression results are still robust.

*Endogeneity Test*

To address the potential reverse causality between the "Broadband China" policy and green sustainable innovation, this paper adopts the instrumental variable method to alleviate the endogeneity problem and ensure the reliability of the empirical results. This paper chooses the logarithm of the city's postal revenue as an instrumental variable for the "Broadband China" policy. On the one hand, postal revenue mainly reflects the utilization of postal services in a city, which has no direct causal relationship with green sustainable

innovation. On the other hand, both postal services and broadband networks are dependent on the development of urban infrastructure and information technology. The implementation and promotion of the "Broadband China" policy will improve the information infrastructure of cities, which will, in turn, promote the development of postal business. Therefore, this instrumental variable satisfies the conditions of being correlated with the explanatory variables and uncorrelated with the error term.

The results in column (2) of Table 3 show the regression results after using citywide postal revenue ($\widehat{kdzg}$) as an instrumental variable. The coefficient is 0.9821 and the t-value is 2.42. This result is consistent with the previous regression results using raw data, indicating that the regression results are still significant and robust after adjusting for endogeneity using the instrumental variable method (2SLS). This further demonstrates the significant positive impact of the "Broadband China" policy on the green sustainable innovation capacity of cities and shows that the endogeneity problem does not seriously affect the empirical results obtained in the previous section.

*Elimination of Extreme Values*

In order to reduce the impact of extreme values on the regression results, we shrink the extreme values of variable values outside the lower 1% and upper 99% quartiles and regress them again. The regression results are shown in column (3) of Table 3. It can be found that the coefficient value of kdzg is significantly positive at the 1% level, which further indicates that the findings are robust.

## Heterogeneity Test

*Heterogeneity of the Level of Openness to the Outside World*

In this paper, the level of openness to the outside world is uniformly divided into three sub-samples of low, medium, and high according to the number of foreign direct investment contract projects in the city. We then re-regress to examine the impact of differences in the level of openness to the outside world on the city's green and sustainable innovation. The results are shown in Table 4. It can be found that the t-values of the "Broadband China" policy in cities with low and high levels of openness to the outside world are 0.03 and 1.63, respectively, which fail the test of significance. The coefficient of the "Broadband China" policy in cities with a medium level of openness to the outside world is 0.2235, with a t-value of 2.24, which passes the significance test at the 5% level. This indicates that the "Broadband China" policy in cities with a medium level of openness to the outside world significantly promotes their green and sustainable innovation capacity.

This may be due to the fact that cities with a medium level of openness to the outside world already have a certain foundation in infrastructure construction, and the "Broadband China" policy can further enhance the network coverage and Internet access capacity of these cities, thus promoting the dissemination and application of green technologies. Additionally, these cities have a certain degree of technological absorption capacity and human capital reserves, enabling them to better utilize the opportunities brought by the new policy to promote green and sustainable innovation. Compared to cities with a medium level of openness to the outside world, regions with a low level of openness usually lag behind in infrastructure development due to a lack of capital [38]. This also limits the effectiveness of policy implementation in these regions and makes it difficult to rapidly enhance green and sustainable innovation capacity. At the same time, these cities have low levels of technological absorptive capacity and human capital, making it difficult to effectively utilize development opportunities for green sustainable innovation even when policy implementation provides them. Cities with high levels of openness to the outside world, although they already have high network coverage and technology levels, may experience diminishing marginal returns from further policy promotion, so the policy effect of "Broadband China" implementation will not be significant in enhancing green sustainable innovation and will not be able to bring about a significant incremental effect.

*Heterogeneity Analysis of Different Resource-Dependent Cities*

According to the "National Sustainable Development Plan for Resource-Dependent Cities (2013-2020)," cities are categorized into five types: growing cities (Type 1), mature cities (Type 2), declining cities (Type 3), regenerating cities (Type 4), and non-resource-dependent cities (Type 5). We re-regressed these five sub-samples, and the results are shown in Table 5. The coefficients of the "Broadband China" policy in Type 2 and Type 5 cities are 0.3067 and 0.1561, respectively, with a t-value of 2.03, passing the 5% significance level test. This indicates that the "Broadband China" policy significantly promotes the green and sustainable innovation capacity of mature resource-dependent cities and non-resource-dependent cities. The t-values of the pilot policy in Type 1, Type 3, and Type 4 cities are -0.55, -0.87, and 1.14, respectively, which do not pass the significance level test, indicating that the "Broadband China" policy fails to significantly promote the green sustainable innovation capacity of growing, declining, and regenerating cities.

The regional energy mix is crucial for fostering sustainable energy practices and supporting the global effort to harmonize human existence with nature [39]. Mature cities are not only able to utilize the economic advantages brought by resources but also

Table 3. Robustness test results.

| Variables | (1) | (2) | (3) |
|---|---|---|---|
| kdzg | 0.1375* | / | 0.1396*** |
| | (1.8) | / | (2.85) |
| dsj | 0.013 | / | / |
| | (0.16) | / | / |
| $(\widehat{kdzg})$ | / | 0.9821** | / |
| | / | (2.42) | / |
| Control Variables | Yes | Yes | Yes |
| Year Fe | Yes | Yes | Yes |
| City Fe | Yes | Yes | Yes |
| N | 3443 | 3449 | 3792 |
| $R^2$ | 0.0202 | / | 0.0689 |

Note: * p<0.1, ** p<0.05, *** p<0.01, t statistics in parentheses; $(\widehat{kdzg})$ are variables after using citywide postal revenue as an instrumental variable.

Table 4. Heterogeneity Analysis of the Degree of Openness to the Outside World.

| Variables | Low Level of Openness | Medium Level of Openness | High Level of Openness |
|---|---|---|---|
| kdzg | 0.1345 | 0.2235** | 0.1357 |
| | (0.03) | (2.24) | (1.63) |
| Control Variables | Yes | Yes | Yes |
| Year Fe | Yes | Yes | Yes |
| City Fe | Yes | Yes | Yes |
| $R^2$ | 0.0086 | 0.0252 | 0.0248 |

Note: * p<0.1, ** p<0.05, *** p<0.01, t statistics in parentheses.

actively seek opportunities for green and sustainable innovation under resource constraints, reaching a relative equilibrium between resource dependence and economic diversification. When the "Broadband China" policy was implemented, digital infrastructure development and urban technology absorption could be effectively combined, creating significant synergies for green and sustainable innovation. Non-resource cities with more diversified economic structures are more likely to benefit from ICT upgrading. These cities tend to have better policy environments and infrastructures, making the implementation of the "Broadband China" policy more effective in promoting green and sustainable innovation. In contrast, the "Broadband China" policy fails to significantly promote green and sustainable innovation in growing cities, possibly due to their relatively homogenous economic structures, resulting in shortcomings in innovation capacity. Declining cities have not been able to effectively implement the policy due to their inability to break away from resource-dependent development paths, weak agglomeration of new factors to promote high-quality development, and the enormous internal and external pressures on resource cities under the carbon emission reduction targets. Regenerating cities may be in the early stages of transformation, with immature industrial restructuring, infrastructure, and technology absorption capacity that need to be upgraded.

## Mechanism Test

In section 4.1, the positive impact of the "Broadband China" policy on green sustainable innovation has been demonstrated. However, the channel through which the "Broadband China" policy affects green sustainable innovation is not yet clear. To verify this transmission mechanism, we analyze the mediating effect using models (3)-(5) and the moderating effect using model (6). The test results are shown in Table 6.

First, according to column (1), the regression coefficient of the "Broadband China" policy on green sustainable innovation is significantly positive

Table 5. Heterogeneity analysis of resource-dependent cities.

| Variables | Type 1 | Type 2 | Type 3 | Type 4 | Type 5 |
|---|---|---|---|---|---|
| kdzg | -0.2549 | 0.3067** | -0.8211 | 0.1587 | 0.1561** |
| | (-0.55) | (2.03) | (-0.87) | (1.14) | (2.03) |
| Control Variables | Yes | Yes | Yes | Yes | Yes |
| Year Fe | Yes | Yes | Yes | Yes | Yes |
| City Fe | Yes | Yes | Yes | Yes | Yes |
| $R^2$ | 0.0309 | 0.0383 | 0.0281 | 0.0361 | 0.0181 |

Note: * p<0.1, ** p<0.05, *** p<0.01, t statistics in parentheses.

(0.1557), indicating that the "Broadband China" policy significantly promotes green sustainable innovation. In column (2), the regression coefficient of the "Broadband China" policy on digitization is significantly positive (1.6720) at the 1% level, indicating that the mechanism by which the policy significantly promotes digitization and thus enhances green sustainable innovation in cities is established. According to transaction cost theory, the implementation of the "Broadband China" strategy promotes the popularization and development of urban Internet, which directly accelerates the flow and dissemination of information, greatly reduces the cost of information acquisition, and facilitates the formation of agglomeration effects. This accelerates the sharing and flow of information and reduces transaction costs. Additionally, the "Broadband China" strategy effectively supports the construction of network platforms by improving the rules and regulations of Internet platforms, which guarantees the smooth development of the platform economy and injects vitality into the acceleration of urban digital transformation. The acceleration of the digital transformation process enhances the value endowment of urban information elements and promotes the sharing of innovative knowledge. By diluting the industrial boundaries in the city and breaking down the technical barriers between industries, it improves information transparency, forcing related industries to continue green innovations to meet public and market demands.

According to column (3), the regression coefficient of the "Broadband China" policy on the energy substitution capacity of cities is significantly negative at the 1% level (-0.3250), indicating that the mechanism by which the policy enhances green sustainable innovation by improving energy efficiency is established. The possible reasons are that the implementation of the "Broadband China" strategy boosts the investment demand of enterprises and consumers within cities, influences the structural transformation of the energy industry through the income effect, price effect, and other pathways, builds the energy digitalization whole industry chain, and enhances energy efficiency. Furthermore, China is vigorously promoting a market-based regulatory system based on carbon emissions trading, energy rights trading, green certificate trading, and green finance, with cities as the main body. This encourages the energy system to strengthen independent intellectual property rights innovation and dynamically upgrade the level of human capital accumulation in enterprises. This requires energy enterprises in cities to enhance green sustainable

Table 6. Mechanism test results.

| Variables | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Growth | szjj | lnrgmq | Growth |
| kdzg | 0.1557** | 1.6720*** | -0.325*** | 1.5535* |
| | (2.25) | (2.83) | (-2.94) | 1.96 |
| lnup×kdzg | / | / | / | -0.1339* |
| | / | / | / | -1.76 |
| Control Variables | Yes | Yes | Yes | Yes |
| Year Fe | Yes | Yes | Yes | Yes |
| City Fe | Yes | Yes | Yes | Yes |
| $R^2$ | 0.0189 | 0.2564 | 0.2961 | 0.0295 |

Note: * p<0.1, ** p<0.05, *** p<0.01, t statistics in parentheses.

innovation capacity by increasing the scale of green R&D and investment in energy-intensive enterprises and green creativity, improving their ability for low-carbon transformation, and continuously reducing the system cost of energy pollution control, which objectively drives urban green sustainable innovation.

According to column (4), the regression coefficient of the "Broadband China" policy on green sustainable innovation is significantly positive (1.5535) at the 10% level. The regression coefficient of the interaction term (lnup×kdzg) on green sustainable innovation is significantly negative (-0.1339) at the 10% level, indicating that a higher number of unemployed people will significantly weaken the effect of the "Broadband China" policy on green sustainable innovation. A high number of unemployed may lead to the loss of high-skilled labor, especially those capable of engaging in green innovation, who may move to other industries or regions, inhibiting the impact of the policy on green and sustainable innovation.

## Conclusions

Based on the panel data of 282 prefecture-level cities in China from 2008 to 2021, this paper analyzes the impact of the "Broadband China" policy on green sustainable innovation using a double-difference model. The main conclusions are as follows. First, the implementation of the "Broadband China" policy can significantly promote green sustainable innovation in pilot cities. Second, the effect of the "Broadband China" policy on green sustainable innovation is more significant in the sub-samples of cities with a medium degree of openness to the outside world, mature cities, and non-resource-dependent cities. Third, the "Broadband China" policy can promote green sustainable innovation through two channels: accelerating the digital transformation of cities and improving urban energy efficiency. Finally, the unemployment rate negatively moderates the relationship between the "Broadband China" policy and green sustainable innovation.

Although this paper explores the impact of the "Broadband China" policy on green sustainable innovation through empirical analysis, it still has the following shortcomings. First, the panel data used in this paper only covers up to 2021, which does not reflect the long-term effect of the policy implementation. Future research can further verify the robustness and generalizability of the findings by extending the time span of the data. Second, although this paper conducted a heterogeneity analysis of cities with different levels of openness to the outside world and resource dependence, it has not yet fully considered the impact of other regional characteristics (e.g., cultural differences, strength of policy implementation, etc.) on the results of the study. In the future, in-depth analysis can be conducted by combining more dimensions of regional characteristics. Additionally, this paper mainly explores two mechanisms—digital transformation and energy efficiency improvement—but fails to comprehensively cover all possible impact paths. Future research can further explore the impact of other potential mechanisms (e.g., innovation ecosystem building, public policy coordination, etc.) on green sustainable innovation.

## Conflicts of Interest

The authors declare no conflict of interest.

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