Assessing the Function of the Technological Finance Cooperation Pilot Policy in China: Effect on Inclusive Green Growth

Guoyong Wu[1] Mengmin Sun[1,*]

1 School of Economics, Guizhou University, Huaxi District, Guiyang 550025, China

Abstract: To attempt to find a win-win path between environmental conservation and economic expansion, it is especially crucial to accurately define the influence of emerging policies on green effects. Based on the dataset of 282 cities at the prefectural level and above from 2010 to 2020, this paper uses difference-in-difference and dual machine learning models to investigate the impact and internal mechanism empirically of pilot policy combining science technology, and finance on inclusive green urban growth. The results show that the policy of the Technology Finance Cooperation Pilot (*TFCP*) has a considerable positive influence on inclusive green growth (*IGG*) in cities, especially when it comes to promoting economic growth and enhancing income distribution. After various robustness tests, the above conclusions are still valid. Meanwhile, from the mechanism analysis results, the policy mainly improves the level of IGG in cities by improving technological progress, enhancing the level of green innovation, and accelerating the development of digital inclusive finance. Furthermore, the impact of the TFCP policy on urban IGG is heterogeneous and mainly depends on the financial condition, geographical location, political status, and industrial characteristics of the city. Further analysis of the spatial effect of policies shows that due to the "siphon effect", the policy of TFCP has an incentive effect on the IGG level of pilot cities, while it has an inhibitory effect on non-pilot cities. Through comprehensive empirical analysis, this study not only strongly validates the positive role of TFCP policy on the IGG of urban economy, but also deeply explores the potential mechanism of this policy, providing new profound insights and enlightenment for policy making.

Keywords: inclusive green growth; **s**cience and technology finance; quasi-natural experiment; dual machine learning; spatial effect

1. Introduction

China's rapid urbanization and industrialization have led to a long period of economic prosperity and remarkable achievements. However, in the context of development in the new era, China's social contradictions have experienced fundamental transformations, and uneven and inadequate development has emerged as the primary problem facing today. To alleviate this contradiction, at the end of 2010, the five departments jointly adopted the "Pilot Implementation Plan for Promoting the Integration of Science and Technology and Finance" (*hereinafter referred to as the "Plan"*), which takes cities as the main subjects of the pilot, and intends to guide the organic integration of science and technology and finance through innovative financial system arrangements, comprehensive use of financial instruments such as free subsidies and loan interest discounts, and transform the mode of economic development innovatively. Provide services for equity financing of small and medium-sized enterprises in science and technology, break through the financing dilemma of science and technology enterprises (Shi et al. 2022), and thus contribute to the sustainable development of the urban economy (Liu and Wang 2023; Leng et al. 2024). Seeking excellent economic growth and building an entirely novel growth pattern are the main themes of current economic development (Du et al. 2024). Different from the single aspect of previous policy

effects, science and technology finance, as an important tool to realize the new development pattern, is an organic combination of a series of financial means and innovative activities, and it is also an emerging economic paradigm. It is deeply in line with the requirements of high-quality development in China's current transformation period and can offer steady support for the green transformation of the urban economy (Hou et al. 2023). As China's economy moves from rapid expansion to sustainable growth, increasing the level of IGG in cities has become critical to fostering high-quality economic growth in China (Fan et al. 2023). As important players in economic development, can cities enhance their IGG through the development of technology and finance? As an important sustainable development policy, has the TFCP policy achieved the expected effect? This is an important question to explore.

Inclusive green growth, as a sustainable development mode that balances environmental friendliness and social equity, is not only a transformation of economic growth mode and path but also a process of institutional reform and mechanism transformation (Wu and Zhou 2021). Compared with the traditional mode of economic growth, IGG has more connotations. It is an organic combination of inclusive growth and green growth, reflecting the triple attributes of efficiency, equity, and environment (Xu et al. 2023). If IGG offers any indication of China's future economic development trajectory, the TFCP policy will play a significant role in propelling that trajectory forward (Wang et al. 2022; Zhao et al. 2024). Current research has given some positive explorations on how it affects economic transformation growth. First of all, the extensive application of science and technology provides technical support for financial development, and the optimization of the financial system also provides a large amount of funds for scientific and technological research and development. The interaction between the two prompts the pilot areas to create a good environment for scientific and technological research and development and loose financial investment and financing conditions, which further solves the technical pain points of related economic entities and alleviates their financing difficulties. To contribute to their economic growth (Wang and Chen 2024; Zhang 2023). At the same time, the TFCP policy can lower the bar for entry into the science and technology finance space, optimize the distribution of financial and scientific resources through government actions, offer financial and scientific support to individuals, micro and small businesses, and other economic entities, and increase the economy's and society's inclusivity (Zhao and Xu 2023). In addition, depending on research and technology to advance technical advancement and modernize the industrial structure, it can promote the wide application of new technologies and new processes, eliminate old industries with backward technology and low efficiency, accelerate the deconstruction and reorganization of traditional industries, and guide the production mode and allocation mode of factors to intensive and green development (Liu et al. 2023; Zhao et al. 2024). It can be seen that the "development opportunity" brought by TFCP policy is not only for the economy itself but also for its inclusive development of micro-economic subjects, as well as its innovation and transformation of traditional industries and green transformation. In light of this, the analysis of the influence and internal mechanism of sci-tech financial policies on IGG in cities not only enriches the exploration of China's economic structural transformation and green development path but also provides a certain reference for the development of relevant international economies, which has important theoretical and practical guiding significance.

Although much research has been done on TFCP policy and IGG, there is still room for further research. Most of the previous studies explored the regional economic development path from a holistic or comprehensive perspective (Awais et al. 2023; Fan et al. 2023), or simply examined the

policy relevance of science and technology finance (Xu et al. 2023; He et al. 2020), insufficient exploration of the cross-links between the two. In addition, although many scholars have adopted single or compound indicators to construct an evaluation system for IGG (Jia et al. 2023; Ofori et al. 2023; Yutian et al. 2024), a unified and reliable evaluation system has not yet been formed, and the standard for measuring IGG has not yet been formed. Additionally, the econometric models involved in current research are more or less faced with the problems of instability and inaccuracy caused by medium- and high-dimensional features or intricate connections, and various endogenous problems brought by this may affect the accuracy of research results.

To address the aforementioned research gaps, this work uses the difference-in-difference (*DID*) and spatial DID methods, as well as the dual machine learning (*DML*) model, to build a quasi-natural experiment based on the TFCP policy using panel data from 282 Chinese cities from 2010 to 2020. The 52 pilot cities involved in the "Plan" are taken as the experimental group. The remaining 230 cities that were not affected by the policy were used as the control group, and the IGG level of Chinese cities from 2010 to 2020 was comprehensively measured from four aspects: economic growth, income distribution, inclusive welfare, and environmental protection and pollution reduction. At the same time, it also examines the impact and internal mechanism of sci-tech finance policies on the IGG of cities and explores the heterogeneity of its influence on different financial development levels, geographical location, political status, and industrial development. In addition, the paper further explores the spatial effect of the technology finance policy and analyzes the effect of the implementation of the policy on non-pilot areas. In conclusion, based on scientific theory and empirical analysis, this study deeply discusses the close connection between the TFCP policy and IGG in cities, and provides a realistic, specific and distinctive reference basis for governments, enterprises and all sectors of society, which helps to better strike a balance between economic growth and environmental protection and promote sustainable inclusive green growth.

The following three areas are where this paper may have a modest impact when compared to the body of previous literature: Firstly, from the perspective of research, this paper changes the previous research paradigm of exploring regional economic development solely from the perspective of external pressure or internal incentives, links TFCP policy with urban economic development, and provides new ideas for improving the IGG and development level of cities. Secondly, in terms of research content, this paper re-measures IGG indicators, supplements and improves the evaluation system of IGG indicators, and theoretically explains three potential channels from the perspective of technological progress, green innovation, and digital inclusive finance, improving and supplementing the existing literature. Finally, regarding research techniques, this work expands the model's application breadth by introducing the DML model into the intersecting disciplines of policy, economy, and environment. At the same time, using the DML model to identify the net effect of TFCP policy on the IGG of cities can alleviate the common endogenous problems to a large extent, making the conclusion more scientific and comprehensive. In conclusion, this study offers fresh insight and guidance for the policy's further execution and enhancement.

The following sections of this essay are arranged as follows. Section 2 focuses on explaining the literature review and hypothesis development. Section 3 introduces the model design of dual machine learning, variable selection, and data sources. Section 4 analyzes and discusses the empirical results in a specific way. Section 5 is a further discussion of the policy spatial effect, and Section 6 gives the conclusions and the policy recommendations. The research process flow chart

in this study was created to effectively illustrate the research procedures, as seen in Fig. 1.

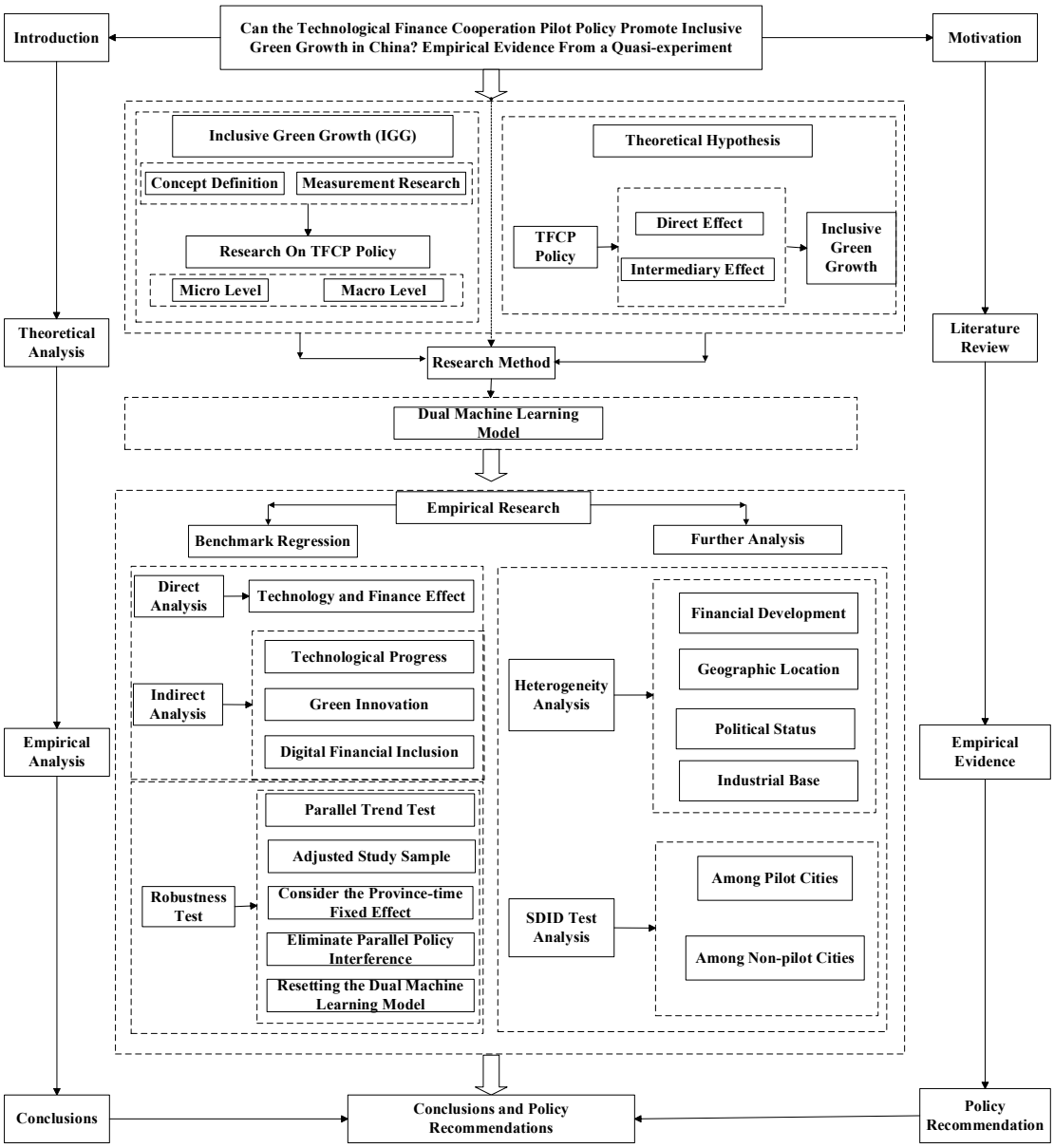

Fig.1. Flowchart of the research progress.

2. Literature review and hypothesis development

2.1. Literature review

In recent years, the research on the IGG has aroused more and more scholars' attention and formed a wealth of research results. The existing research mainly discusses the IGG of the urban economy from the following aspects. The first is the research on the connotation of the IGG. Albagoury (2016) described inclusive green growth in terms of the environment, stressing the preservation of natural resources and environmental protection in the context of ecological balance, while also incorporating the idea of "sustainable development". Berkhout et al. (2018) pointed out that the IGG should also include the ability to increase the well-being of present and future generations. Zhao et al. (2023) proposed that the IGG aspires to improve social welfare while promoting environmental sustainability and social fairness. The second is the measurement of the

IGG. Various approaches have been employed to measure the level of inclusive green growth. Ali and Son (2007) tried to use the social opportunity function as a tool for assessing the level of inclusive development, offering new insights for subsequent studies. The five elements of economic development, people's welfare, social equity, green production and consumption, and ecological environment protection were used by Wu and Zhou (2019) to measure the level of IGG completely and accurately. Jia et al. (2023) employed the super-EBM model, which is based on the input-output perspective, to measure IGG holistically from several angles, including public health cost, environmental governance input, and social consequences. Stojkoski et al. (2023) examined the impact of complexity indicators on IGG and utilized an economic complexity approach to explain regional and global variations in IGG. Ofori et al. (2023) constructed a research framework for the IGG by capturing the core components of social progress and environmental sustainability. However, although many scholars have adopted single or compound indicators to build an evaluation system for the IGG, a unified and reliable evaluation system has not yet been formed, and the standard for measuring it has not yet been formed (Sun et al. 2020; Li et al. 2023). Based on this, the measurement analysis of IGG in this paper will enhance the existing analytical framework and have certain theoretical innovation value.

The third is to investigate how different factors affect the IGG. After reviewing numerous kinds of literature, it can be found that, first of all, the development of inclusive green cities is significantly impacted by institutional and institutional reforms (Desalegn and Tangl 2022). For example, Schoneveld et al. (2015) and Song et al. (2018) found that fiscal decentralization and economic system reform have significant promoting effects on IGG. Secondly, IGG in cities is significantly impacted by changes in technology as well. Chen et al. (2020) and Guan et al. (2022) believe that the combination of technological changes and technological efficiency can affect IGG levels in cities. Wu et al. (2023) discuss the impact of industrial intelligence on IGG and believe that it can contribute to IGG through industrial structure upgrading, education, and financial development. In addition, some scholars have also pointed out the factors that hinder the IGG level of cities, such as the uncertainty of economic policies (Gu et al. 2021), government intervention (Fan et al. 2023), and the mismatch between land and finance (He and Du 2022).

In light of the high return of modern technology and the profitability of financial capital, these two factors together can, to a certain extent, encourage innovation in science and technology as well as the application of research findings and play a crucial role in fostering IGG (Yao et al. 2021). For this reason, in 2011 and 2016, the Chinese government started implementing a trial program for technical finance, respectively, which aims to modify the economic development model in a creative approach to support IGG and integrate regional technological and financial growth. In addition, since the introduction of the TFCP policy, academics have paid close attention to it, and several experts have undertaken substantial research on TFCP policy, and the relevant research mainly centers on two levels. On the one hand, the research is based on the micro level, which mainly discusses the financing constraints of technological finance on enterprises (Wang and Chen 2022; Zhang 2023), factor resource allocation efficiency (Zhao and Xu 2023), innovation performance, enterprise competitiveness (Xu 2022) and green transformation (Xu et al. 2023). On the other hand, there are macro-level studies, which mainly investigate technology and finance's regional innovation ability (Pang et al. 2020), total factor productivity (Lu et al. 2023), carbon emission reduction performance (Xu et al. 2022; Hou et al. 2023), and sustainable development of the economy (Liu et al. 2022a; Liu et al. 2023). Among them, the literature has given a positive answer

based on different perspectives on whether TFCP policy can promote IGG in urban (Jiang et al. 2022). In addition, Liu et al. (2022b) and Sheng et al. (2021) argue that TFCP policy can promote regional economic development by triggering technological progress. He et al. (2020) find that TFCP policy can promote regional economic development through technological advancement. Moreover, based on the perspective of environmental improvement, Liu et al. (2021a) believe that by increasing the effectiveness of resource use, technological finance cooperation may enhance regional economic development.

To sum up, the research results of the existing literature provide a large number of ideas for reference and theoretical support for the creation of this paper. However, unfortunately, although the existing literature affirms the positive significance of science and technology finance for economic development and affirms that IGG will become the trend of economic development in the future, the research on the relationship between the two is insufficient. At the same time, there are still large differences in the measurement and impact mechanism of IGG. Therefore, it is necessary to re-measure IGG indicators and cross-study the two-way impact of TFCP policy and IGG, which is crucial to the development of China's urban economy.

2.2. Hypothesis development

The adoption of the TFCP policy has made it possible for the financial capital chain and the science and technology innovation chain to naturally combine, and it has also indicated a new path for the growth of the IGG of city economies. On the one hand, the adoption of the policy on TFCP can encourage the effective integration of city science technology, and finance, which not only enhances the degree of city scientific and technology innovation but also promotes city finance growth (Zhao and Xu 2023). This is mainly reflected in the fact that the TFCP policy promotes the government of the pilot city to obtain the preferential financial capital policy, relaxes the investment and financing conditions of local financial institutions, alleviates the financing pressure of urban economic development, promotes the exploration of new development models and new development directions in the pilot areas, and effectively promotes the upgrading and rationalization of the industrial structure, and then encourage the urban economy's superior development (Huang et al. 2017). In addition, it is important to note that when fostering the transformation of the industrial structure (You and Zhang 2022), science and technology finance can also promote the improvement of labor productivity and generate a large number of new jobs, thus promoting the development of tertiary industry and high-tech industry, improving the income level of urban and rural residents, and improving urban and rural income distribution. It embodies the inclusive characteristics of economic growth (Chen et al. 2023; Zeng et al. 2023). On the other hand, technology and science financing can also help progress new-generation digital technologies like big data, reduce the information barriers and technical constraints in the traditional development mode (Laeven et al. 2015), help the region to carry out digital transformation, improve resource utilization efficiency, and promote the progress of pollution control technology. Guide the green transformation of production mode (Liu and Wang 2023). Considering this, this study puts forth hypothesis 1:

Hypothesis 1. The TFCP policy can promote IGG in cities in pilot areas.

TFCP policy can promote IGG in cities by promoting technological progress. Specifically, science and technology finance can optimize the allocation of science and technology resources through government behavior and innovative financial innovation investment methods, thus enhancing the independent innovation capability of pilot areas and promoting the improvement of

technology level (Ji et al. 2024). There are two primary ways that technical advancement mediates the promotion of IGG in cities. On the one hand, technological progress will bring about the wide application of new technologies, new equipment, and new processes. With the continuous emergence of new technologies, a large number of old industries with backward technology, low efficiency, and poor quality have been impacted and eliminated, while emerging industries continue to rise, and the efficiency of resource allocation has been improved (Liu et al. 2024a). Simultaneously, the ongoing modernization of the industrial structure propels the urban economy's continued growth (Jaffeet et al. 2002). In addition, the mass production of machines brought about by technological progress has replaced some high-risk jobs and boosted the accumulation and upgrading of human capital to a certain extent. From this perspective, technological progress reflects the inclusive characteristics of economic development (Wei et al. 2016). On the other hand, technological progress raises the technological entry threshold of the industry, and guides and encourages the production body to prefer cleaner production with higher productivity (Wang and Chen 2024). From this perspective, technological progress can guide the green development trend of the industry. Thus, hypothesis 2 is put forth:

Hypothesis 2. The TFCP policy can promote IGG in cities by promoting technological progress.

The intermediary role of green innovation in IGG primarily appears in the term "green". Green development is the due meaning of high-quality economic development, and green innovation is a crucial way to support green development (Fosu et al. 2024). Due to its dual attributes of "environmental protection" and "innovation", it is prone to problems such as high risk and high cost, and the implementation of TFCP policy can alleviate the above problems, thus laying the tone of green development. On the one hand, scientific and technological progress determines the direction of technological innovation, and the implementation of relevant policies can provide more innovation resources for pilot cities, attract more high-level talents to gather in pilot cities, and accumulate a good foundation to further the growth of urban green innovation (Tang et al. 2024a). On the other hand, by influencing the flow of financial resources, the financial policy of science and technology can restrain the environmentally unfriendly behaviors of the economy, guide the green development tendency of various industries by increasing the investment in green innovation, and promote the green transformation of the economy (Zhang et al. 2024). In addition, the technology finance policy can also give play to the advantages of the government, strengthen the environmental supervision inside the pilot cities (Dong et al. 2024), improve the public's environmental awareness, and guide the green development direction of the urban economy. Regarding this, this paper presents hypothesis 3:

Hypothesis 3. The TFCP policy can influence IGG in cities by promoting green innovation.

The traditional financial business is affected by the constraints of geographical space, mainly close transactions, and the scope of financial services is limited. However, the application of the TFCP guidelines has broken the shackles of science technology, and finance and brought more favorable financial development support and a scientific and technological innovation atmosphere to pilot cities (Ding et al. 2021). On the one hand, the policy can attract capital investment and the concentration of R&D talents, and encourage the coordinated development of science, technology, and finance by fully exploiting the advantages of various resources such as people and property, and realize the optimal allocation of financial resources, creating conditions for the growth of digital inclusive finance (Ma 2023; Chang et al. 2024). On the other hand, implementing the TFCP policy, with its technical and financial advantages, can improve the breadth and extensibility of financial

services while lowering the service cost of inclusive finance (Ren et al. 2022; Razzaq et al. 2023), so that more high-quality and personalized services can benefit more residents, and further strengthen the inclusive characteristics of economic development. In addition, the growth of the financial industry is intimately tied to the city's overall economic development (Duarteal et al. 2012). The natural fusion of conventional finance and digitalization can promote distinctive development vigor, contribute significantly to closing the gap between urban and rural development, and lessen poverty (Feng et al. 2022; Suhrab et al. 2024). Given this, hypothesis 4 is put out in this paper:

Hypothesis 4. The TFCP policy can influence IGG in cities by promoting the growth of digital financial inclusion.

The implementation of the pilot policy is an efficient system for China to try first. Relying on the policy advantages, the pilot areas can get rapid development in a short period. According to the "center-periphery" theory, the favorable effects of pilot policies on pilot areas will appear in central areas, and the spatial effects are more obvious in peripheral areas (Huang et al. 2022). Studies on the spatial effects of policies have further derived two competing views: One is the "spillover theory" (Niu et al. 2024; Wang et al. 2024), which emphasizes the spillover effect, and this holds that the pilot policy's execution can have a radiation-driven role in addition to encouraging local area development (Tang et al. 2024b), so that the non-pilot areas can take advantage of its policy spillover effects to achieve a certain degree of development through the cross-regional flow of capital and the spatial reorganization of industries (Lu et al. 2023). The other is the "siphon theory" (Zhou et al. 2019), which emphasizes the siphon effect. According to this theory, due to the existence of policy advantages, the implementation of pilot policies may attract funds, talents, and other resources from non-pilot areas to flow to the pilot areas, resulting in resource outflow from non-pilot areas. Inhibit its further development (Bian et al. 2024). Therefore, as one of the pilot policies, the TFCP policy has uncertain effects on the IGG of cities in non-pilot areas. Accordingly, the following study hypothesis is put out in this paper:

H5a: The TFCP policy as a whole will promote IGG in non-pilot cities.

H5b: The TFCP policy as a whole will inhibit IGG in non-pilot cities.

To clearly illustrate the research hypothesis, we draw a flow chart of the research hypothesis, as shown in Fig. 2.

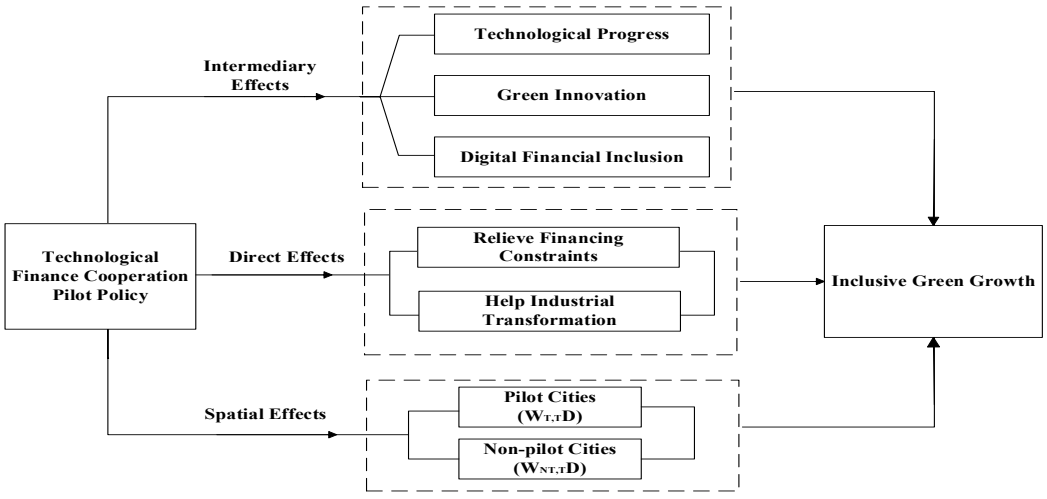

Fig.2. Influence Mechanism analysis diagram.

3. Research design

3.1. Modeling

Since the implementation of the TFCP policy, there has been a proliferation of literature evaluating the effects of the policy, and a wealth of research results have been achieved. However, the majority of the existing work on assessing policy effects employs standard causal inference models (Tang et al. 2022; Xia et al. 2023), which have many limitations on the requirements of sample data and the selection of matching variables. Given this, to overcome the limitations of traditional causal inference models and break the traditional assumption of the spatial complexity of object parameters, machine learning methods have gradually attracted extensive attention from scholars (Zhang et al. 2022). The dual machine learning model formed by combining the traditional causal inference model with the machine learning method by relevant scholars provides a more effective method for formally and accurately estimating and inferring causal parameters in highly complex environments and can break away from the traditional frameworks considered in the classical semi-parametric literature to accurately estimate the parameter coefficients in high-dimensional parameter cases when inferring causal parameters. Specifically, the related literature on the use of dual machine learning models includes two main aspects, on the one hand, the innovation of theoretical methods based on the DML to improve the validity of the high-dimensional parameter estimation results and to enrich the dynamic quantization extensions of dual machine learning (Chiang et al. 2022; Bodory et al. 2022). On the other hand, it is to assess and quantify causality in economic phenomena by applying dual machine learning models (Farbmacher et al. 2022; Zhang et al. 2022).

The preceding study on evaluating parameter coefficients using a DML model has made a significant contribution to the effective evaluation of policy effects (Liu et al. 2024b; Wen et al. 2024). This is primarily because the model uses regularization to reduce variance and over-fitting to ameliorate regularization deviation, and thus effectively rediscusses traditional semi-parametric reasoning of low-dimensional parameters in the presence of high-dimensional parameters (Chernozhukov et al. 2018). In addition, since regularization bias and overfitting in estimating parameters can lead to serious bias in the estimates, Chernozhukov et al. concluded that the effects on the estimates can be eliminated by (1) estimating θ_0 using Neyman-orthogonal moments, which are less sensitive to nuisance parameters, and (2) utilizing cross-fitting, proving a useful technique for data-splitting. The advantages of the DML technique are that, firstly, it eliminates the dimensionality issue caused by classical linear regression's overabundance of control variables. and secondly, that there is no need to preset the relationship between the variables, and that the precision of the path for handling nonlinear relations is enhanced. Obviously, this method shows obvious advantages in dealing with nonlinear and high-dimensional variables, and can estimate the causal effect more accurately.

In this study, the selection of the DML model has many advantages in variable selection, model estimation, and robust results. First of all, IGG is a comprehensive indicator to measure urban economic development, which is affected by many human factors such as economic, social, or political factors. To improve the accuracy of policy effects, other factors affecting urban economic development should be controlled as much as possible. However, high-dimensional variables are challenging to effectively control in the traditional model due to the "dimensional curse" issue. The superiority of the DML model in controlling high-dimensional variables is highlighted. Secondly, the DML model also has advantages in processing nonlinear data, which can effectively alleviate the model deviation problem (Yang et al. 2020; Zhou et al. 2024). Based on this, this paper refers

to relevant studies (Zhang and Li 2023; Wen et al. 2024), considering the impact of TFCP on IGG in cities under the dual machine learning framework.

Firstly, this paper uses the DML method to construct a partial linear regression model, and makes an empirical analysis based on it. The details are as follows:

$$\begin{aligned} IGG_{it+1} &= \theta_0 Event_{it} + g(X_{it}) + U_{it} \\ E(U_{it} \mid Event_{it}, X_{it}) &= 0 \end{aligned} \tag{1}$$

where i is the city, t is the year. IGG_{it+1} denotes the explanatory variable, for the IGG of the city's economy. $Event_{it}$ is the policy variable of the TFCP, which is 1 after the pilot is set, otherwise it is 0. θ_0 is the coefficient of disposition that is the focus of this paper. X_{it} is the multidimensional control variable of city i in year t, including education and science and technology investment, urbanization level, and industrial structure, etc. The estimator $\hat{g}$ of g is obtained through the machine learning model. U_{it} is the error term with a conditional mean of zero.

The estimator $\hat{\theta}_0$ that results from directly estimating equation (1) is biased. This is considering that in high-dimensional model settings, regular terms are frequently used to lower the dimension. However, the introduction of regular bias may make it difficult for $\hat{\theta}_0$ to converge to the real θ_0. Fortunately, the introduction of auxiliary equation (2) may improve the above problems.

$$\begin{aligned} Event_{it} &= m(X_{it}) + V_{it} \\ E(V_{it} \mid X_{it}) &= 0 \end{aligned} \tag{2}$$

where $m(X_{it})$ represents the regression function of disposal variables to high-dimensional control variables, and its specific form $\hat{m}(X_{it})$ needs to be estimated with the help of machine learning algorithm. V_{it} represents the error term, and its conditional mean is 0.

The steps are as follows. Initially, the auxiliary regression $\hat{m}(X_{it})$ is estimated using a machine learning technique, taking its residuals $\hat{V}_{it} = Event_{it} - \hat{m}(X_{it})$. Second, the same algorithm is used to estimate $\hat{g}(X_{it})$ that changes the form of the main regression to $IGG_{it+1} - \hat{g}(X_{it}) = \theta_0 Event_{it} + U_{it}$. Finally, taking $\hat{V}_{it}$ as the tool variable of $Event_{it}$, after determining the estimator $\hat{g}$ of function g using the machine learning model, the estimated value $\check{\theta}_0$ of θ_0 is determined, this is:

$$\check{\theta}_0 = \left(\frac{1}{n} \sum\nolimits_{i \in I, t \in T} \hat{V}_{it} Event_{it} \right)^{-1} \frac{1}{n} \sum\nolimits_{i \in I, t \in T} \hat{V}_{it} (IGG_{it+1} - \hat{g}(X_{it})) \tag{3}$$

where n is the total sample size and the other parameters are consistent with the above equation.

Similarly, equation (3) can again be approximated as:

$$\begin{aligned} \sqrt{n}(\check{\theta}_0 - \theta_0) &= [E(V_{it}^2)]^{-1} \frac{1}{\sqrt{n}} \sum\nolimits_{i \hat{I} I, t \hat{I} T} V_{it} U_{it} \\ &+ [E(V_{it}^2)]^{-1} \frac{1}{\sqrt{n}} \sum\nolimits_{i \hat{I} I, t \hat{I} T} [m(X_{it}) - \hat{m}(X_{it})][g(X_{it}) - \hat{g}(X_{it})] \end{aligned} \tag{4}$$

where $[E(V_{it}^2)]^{-1} \frac{1}{\sqrt{n}} \sum_{i \in I, t \in T} V_{it} U_{it}$ obeys a normal distribution with a mean 0. Since two machine learning estimations are used, the overall speed of convergence of

$[E(V_{it}^{2})]^{-1}\frac{1}{\sqrt{n}}\sum_{i\in I,t\in T}[m(X_{it})-\hat{m}(X_{it})][g(X_{it})-\hat{g}(X_{it})]$ depends on the speed of convergence of $\hat{m}(X_{it})$ to $m(X_{it})$ and $\hat{g}(X_{it})$ to $g(X_{it})$, i.e., $n^{-(\varphi_g+\varphi_m)}$, where $\sqrt{n}(\breve{\theta}_0-\theta_0)$ converges faster to 0, which in turn allows for unbiased estimates of the coefficients of disposition.

3.2. Variable setting and selection

3.2.1. Explained variable

To scientifically evaluate the impact of TFCP policy on IGG in cities, it is necessary to measure the level of IGG in cities. Based on relevant literature and city-level data (Zhou et al. 2020; Zhao and Xu 2023; Li and Tong 2024), a comprehensive economic IGG indicator system is constructed, which includes four dimensions, that is, economic growth (*EG*), income distribution (*ID*), welfare benefits (*WB*) and environmental protection and pollution reduction (*PR*). Intending to accurately reflect the fluctuations in economic growth at the city level in China, this indicator system measures economic growth using GDP per capita and GDP growth rate (Hunjra et al. 2022). In addition, using the relevant literature for reference, income distribution is measured using the per capita disposable income of urban and rural people, as well as the ratio of per capita disposable income of urban and rural residents. The universal benefits of welfare are measured by the number of participants in basic medical care and basic old-age insurance in urban areas, the ratio of unemployment insurance participants to the total population at the end of the year, the number of public library books per 10,000 people, and the number of beds in hospitals and hospitals. Industrial soot emissions, industrial wastewater emissions, industrial sulfur dioxide emissions per 10,000 people, complete industrial solid waste utilization, centralized sewage treatment plant treatment rates, and harmless household waste treatment rates are used to quantify environmental protection and pollution reduction. Finally, the IGG of the urban is calculated using the subjective and objective combination weighting approach. Simultaneously, to highlight the movement of the index, the evaluated index is mapped to 0~10. Furthermore, given the convenience of access to data indicators, this paper plans to set the scope of the study to 282 cities in China from 2010 to 2020, and mainly rely on the "China Urban Statistical Yearbook" as the source of relevant data. The essential IGG measurement indicators are provided in Table 1.

Table1

Indicators for IGG.

Goal	Dimensionality	Index	Unit
Inclusive Green Growth Index	Economic Growth	Gross national product per capita	ten thousand yuan
		Growth rate of gross national product	%
	Income Distribution	Per capita disposable income of urban residents	yuan
		Per capita disposable income of rural residents	yuan
		Ratio of per capita disposable income of urban and rural residents	%
	Inclusive Welfare	The proportion of urban basic medical insurance participants to the total population at the end of the year	%
		The ratio of the number of urban basic old-age	%

		insurance participants to the total population at the end of the year	
		The ratio of the number of urban basic unemployment insurance participants to the total population at the end of the year	%
		Number of public library books	piece
		Number of beds in hospitals and health centers	single
	Environmental Protection And Pollution Reduction	Industrial sulfur dioxide emissions	ton
		Industrial wastewater discharge	ten thousand tons
		Industrial soot emission	ton
		Comprehensive utilization rate of general industrial solid waste	%
		Centralized treatment rate of sewage treatment plant	%
		Harmless treatment rate of household garbage	%

3.2.2. Explanatory variable

In the Programme, a total of 16 regions were selected. Due to the situation of "one region and many cities", this paper is further subdivided into 43 pilot cities, to break through the financing bottleneck of regional economic development. Since then, to further accelerate the implementation of the innovative development strategy, nine new cities such as Zhengzhou and Xiamen have carried out pilot work in 2016. So far, a total of 52 cities have been included in the scope of the TFCP policy. In this paper, 52 pilot cities were taken as the experimental group, and the remaining 230 cities that were not affected by the policy were taken as the control group. According to the implementation time of the pilot cities, the policy dummy variable (*did*) of the "science and technology finance" pilot was constructed to analyze and verify whether the policy could promote the IGG level of the pilot areas.

3.2.3. Control variables

According to traditional regional economic theory, factors affecting regional comprehensive development include geographical advantage, resource endowment, and industrial agglomeration (Miar et al. 2024; Yang et al. 2024), combined with the study in this paper, we can see that in the process of regional economic development, factors such as culture, education, science and technology, finance and human capital are closely related to regional economic development, and changes in relevant factors can make the regional economic development different. Therefore, it is necessary to control the above factors to assess the net effect of technology finance policies on IGG in pilot cities and provide more accurate results to the maximum extent. To sum up, this study follows the existing literature (Ma et al. 2023; Guo and Liu 2022; Kohler et al. 2024), and selects the following control variables: Local market competition is measured by the fiscal revenue-to-expenditure ratio (*Lgg*). The quantity of books overall per 10,000,000 volumes in public libraries is used to quantify cultural resources (*Cr*). The natural logarithm of the number of persons per 10,000 square kilometers is used to calculate administrative area (*Aa*). The ratio of educational spending to regional GDP serves as a measure of educational investment (*Edu*). The ratio of regional GDP to scientific and technological expenditures serves as a proxy for scientific and technological investment (*Sci*). The natural logarithm of the number of persons per square kilometer is used to

determine the degree of urbanization (*Urban*). The ratio of total retail sales of consumer goods to regional GDP is used to calculate consumption (*Consump*). The industrial structure is proxied by the value-added ratio of the tertiary sector to the secondary sector (*Constru*) (Guo and Liu 2022; Liu et al. 2021c). The level of unemployment is calculated by dividing the number of persons who were officially unemployed in cities and municipalities at the end of the year by the total population (*Unemp*). To quantify fixed asset investment, the ratio of total fixed asset investment to regional GDP is employed (*Inv*). The proportion of global Internet users to the total population at the end of the year is used to gauge Internet penetration (*Inter*). The ratio of last year's balance of financial institutions' deposits and loans to the local GDP serves as a gauge of their financial size (*Size*). The natural logarithm of the number of students in elementary, middle, and other schools per 10,000 inhabitants is used to calculate human capital (*Cap*). The transportation level is measured by the natural logarithm of road passenger volume (*Pass*) and road freight volume (*Fre*). The proportion of individual and private employees to all industrial employees indicates the degree of privatization (*Pri*). All of the data stated here were sourced from the China Urban Statistical Yearbook. Furthermore, to improve the accuracy of the fitting model, this research incorporates the quadratic term of each city variable into the regression analysis. Simultaneously, we introduce the fixed influence of city and time in the form of individual and annual virtual variables.

3.2.4. Mechanism variables

This paper intends to reveal the mechanism effect of TFCP policy on urban economic IGG from three paths including technological progress effect, green innovation effect, and digital inclusive financial development. Among them, Patent application is the micro expression of technological progress. This paper uses the natural logarithm of the patent application to measure the technological progress of cities (*Patent*). Green patent data can directly reflect the green innovation activities in the region. This paper uses the natural logarithm of the number of green invention patent applications to measure the green innovation of each city (*GPatent*). Furthermore, the China Digital Financial Inclusion Index (*DFII*) and its sub-indices, such as Breadth of coverage (*Breadth*), Depth of application (*Depth*), and Digitization, are used to track the progress of digital financial inclusion in cities. It should be noted that the data on technological progress and green innovation come from the China Urban Statistical Yearbook, and the Digital Financial Inclusion index comes from the Digital Financial Inclusion Research Center of Peking University.

4. Empirical analysis

4.1. Benchmark regression

By using the DML model, this paper deeply discusses the policy effect of TFCP on urban IGG. To predict and solve the results of principal regression and auxiliary regression more accurately, this paper also uses the random forest algorithm, and sets the sample segmentation ratio at 1:4. The regression results are shown in Table 2. Column (1) in the table is a primary term controlling for city-fixed effects, time-fixed effects, and other city variables in the full sample interval. The regression coefficient of the TFCP policy on the IGG of the urban is considerably positive at the 1% level, showing that it may contribute to the IGG of the urban. Next, column (2) in the table further controls for the quadratic term of the urban variable based on column (1), whose regression coefficient is still significantly positive and has little change in value. Additionally, since the data on disposable income of rural residents are missing more before 2014, this paper interpolates this data for each city, based on which, intending to prevent interpolation errors from interfering with

the regression results, this paper narrows the sample interval to the period 2014-2020 according to the explanatory variables based on the data in the first two columns and conducts the regression, and the results of the regression are shown in Column (3) and Column (4) in the table. It can be found that after adjusting the regression interval, the regression coefficient of the TFCP policy on the IGG of urban still shows a significant positive impact, and the regression coefficient has increased, which does not change the previous conclusion. This indicates that TFCP policy plays a significant policy effect in promoting IGG levels in cities, which confirms previous relevant studies (Leng et al. 2024; Mehmood et al. 2024), thus H1 can be verified.

Table 2

Benchmark regression results.

Variables	(1) IGG	(2) IGG	(3) IGG	(4) IGG	(5) EG	(6) ID	(7) WB	(8) PR
did	0.186***	0.189***	0.218***	0.219***	0.270***	0.333***	0.0105***	0.046
	(0.038)	(0.038)	(0.056)	(0.056)	(0.059)	(0.087)	(0.032)	(0.061)
Control variable a term	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control variable quadratic term	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2820	2820	1974	1974	2820	2820	2820	2820

*Note: *, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively, with robust standard errors in parentheses. The following tables are the same as.*

To learn more about how the TFCP policy has affected the components of IGG of the urban, the regression coefficients of the TFCP policy on economic growth, income distribution, welfare inclusion, and environmental protection and pollution reduction are given in columns (5) to (8) of Table 2, respectively. As far as the policy effects are concerned, the impacts of the TFCP policy on urban economic growth, income distribution, and welfare inclusion are all significantly positive at the 1% level, with the regression coefficient (0.333) on income distribution being the largest. This suggests that the TFCP policy promotes urban economic growth, income distribution, and welfare inclusion, as well as the liberalization of the technology finance industry's entrance threshold as a result of the reform of the technology financial sector, which increases the job opportunities for urban workers, coupled with the resulting rise of new science and technology enterprises, which further expands the choice of jobs for urban workers, thus contributing to the enhancement of the quality of employment of urban residents and has a direct effect on the pattern of income distribution (Chen et al. 2023; Zeng et al. 2023). In addition, as a policy instrument, the TFCP policy is not directly involved in the production process, and the producers combine this policy with other factors to improve the allocation of factors of production, indirectly increasing economic output and welfare inclusion. Therefore, compared with economic growth and welfare inclusion, the TFCP policy has a greater impact effect on income distribution (Wei et al. 2016). In addition, the regression

coefficient of the TFCP policy to environmental protection and pollution reduction is positive but not significant, which shows that the TFCP project does not significantly affect the IGG of the urban. The reason may be that although the pilot of technological finance cooperation is conducive to guiding industrial agglomeration and green development and realizing the intelligence and efficiency of environmental governance (Wang and Chen 2024; Tang et al. 2024b), at the same time, the basic materials and all kinds of power waste that are constantly eliminated as a result of the pilot of technological finance cooperation will also aggravate the level of environmental pollution, and the aforementioned two impacts cancel one other out, making the overall impact of the TFCP policy on lowering urban environmental pollution negligible.

4.2. Robustness Tests

4.2.1. Parallel trend test

A detailed parallel trend test is conducted in this paper, aiming to explore in depth whether the changing trend of the IGG index of the treatment group and the control group is consistent prior to the start of TFCP policy. Through this test, this paper hopes to understand the potential differences between the two groups before the policy's execution more accurately, to provide a more reliable basis for the subsequent assessment of policy effects. Since the cities implementing the policies were set up in batches in 2011 and 2016, the implementation time of the policies in different cities was different, so the time dummy variable was set, and its value was the difference between the current year and the year in which the TFCP policy was implemented. The value of the year in which the policies were implemented was 0, that of the previous year was -1, and that of the following year was +1. Since the study period of this paper is 2010-2020, the value range of dummy variables is [-6,8], which avoids multicollinearity and maintains the balance of data (Marx et al. 2024; Chen et al. 2024), referring to relevant studies, this paper sets the relative years of other cities that are larger than 6 years as 6, and deletes the virtual variables in this period, as shown in Figure 3. The findings demonstrated that, before the policy's implementation, the estimated coefficients for each period had no significant difference from 0 (Xu et al. 2024), and the estimated values of the coefficients were also not significant, indicating that, before the policy's implementation, there was no significant difference in the IGG levels between the experimental and control groups, supporting the hypothesis of a parallel trend.

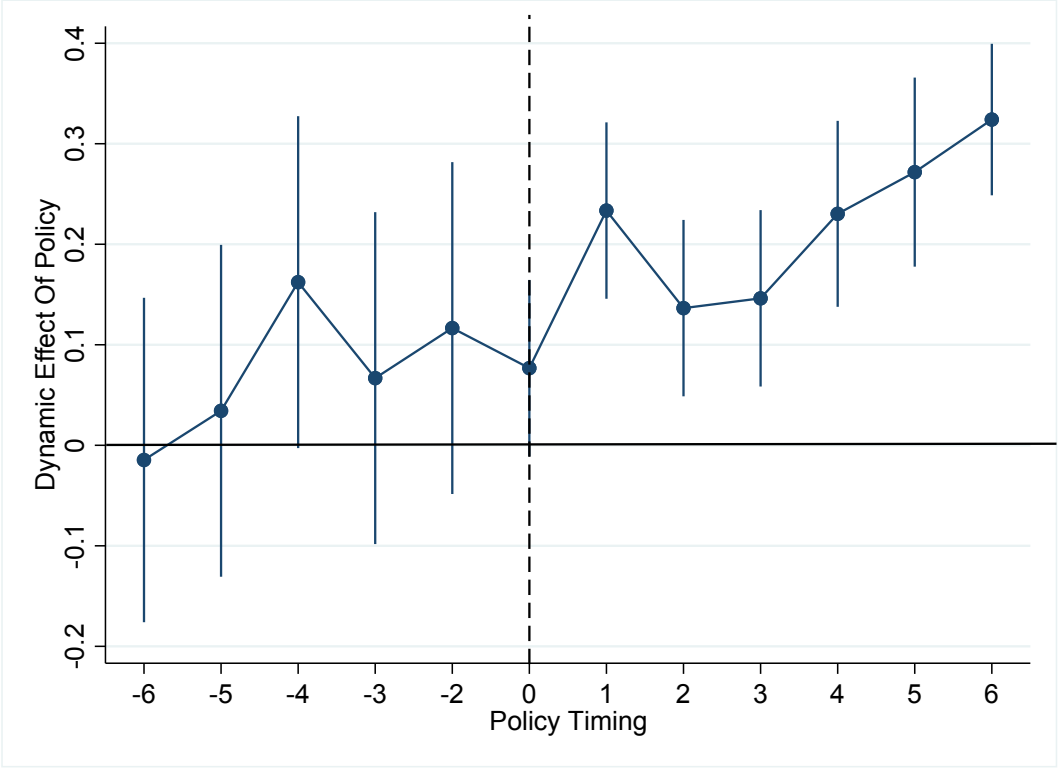

Fig.3. Parallel trend test chart

4.2.2. Removal of outliers

Outliers in the regression samples may lead to biased estimation results, especially for the urban economic IGG index synthesized through the portfolio assignment method. Based on this, in addition to the disposal variables, the rest of the variables in the benchmark regression are tailed by 1% and 5% quantiles, and the values higher than the highest quantile and lower than the lowest quantile are eliminated, and the regression analysis is redone with the processed data. Table 3 displays the results of the regression. It can be shown that even when the aberrant numbers are taken into account, the regression findings are still significant, and the paper's conclusion is still valid.

4.2.3. Adjusting the research sample

There is a big gap in the science and technology financial foundation of different provinces and cities. Therefore, this paper excludes seven provinces and cities with poor science and technology financial foundations in 282 cities, including Gansu, Qinghai, Ningxia, Xinjiang, Tibet, Yunnan and Guizhou, and excludes the four municipalities with good development foundations, including Beijing, Tianjin, Shanghai, and Chongqing, and retains the samples of other cities for regression analysis (Li et al. 2022a; Li et al. 2022b). Table 3 presents the specific regression results, and it is evident that even when some of the research samples are taken into consideration, the regression coefficient of the TFCP policy to the IGG of the urban economy remains significantly positive at the level of 1%, demonstrating the reliability of the benchmark mentioned above regression results.

4.2.4. Exclusion of similar policy effects

When the IGG of the urban economy is being evaluated by the program of TFCP, other related policies will unquestionably result in an overestimation of the impact of policy execution. The preceding literature is cited in this study to help solve this issue, and additional related strategy variables are included in the baseline regression model. After 2010, with the implementation of the

TFCP policy, its related national innovation city pilot policy (*Innovationcity*), national autonomous innovation demonstration zones (*Auto-Innocity*), and the pilot policy of smart cities (*Smartcity*) were also launched in 2010 and 2013, respectively. This article makes the case that the aforementioned measures will influence the IGG of the urban economy. To analyze the overall impact of TFCP policy, it is, therefore, more suitable to include the creation of innovation cities, independent innovation demonstration zones, and smart cities in the benchmark regression model. As evidenced by the outcomes in Table 3, innovative city construction, pilot autonomous innovation demonstration zones, and smart city construction have a profoundly favorable effect on the IGG of the urban economy, with smart city construction having the most significant impact. Meanwhile, after adding the policy dummy variables of innovation city pilot, independent innovation demonstration zone, and smart city pilot into the regression analysis, the influence of TFCP policy remains significant, but the coefficient value decreases, indicating that the impact of TFCP policy on urban economy IGG may have been overestimated. However, it still has a major enabling effect.

4.2.5. Considering province time interaction fixed effects

In the baseline regression, we solely account for fixed effects such as city and time. However, the province where the city is located will also introduce a series of local regulations at different times to promote the IGG of the region's economy, which is likely to give rise to policy heterogeneity across provinces, which will affect the IGG of the city's economy in different provinces. Therefore, we adjust for the interaction fixed effects of province time and run the regression once more to ensure that these factors do not interfere. In column (3) of Table 3, the specific regression findings are displayed. After adjusting for the provincial time fixed effects, it is observed that the regression coefficient is still significantly positive, and this result is similar to the previous benchmark regression result. This finding further confirms the robustness of the conclusions of this paper.

Table 3

Robustness test.

Variables	（1） Adjusted study sample	（2） Tailing treatment 1% tailing	（2） Tailing treatment 5% tailing	（3） Consider the province-time fixed effect	（4） Eliminate parallel policy interference			
did	0.185*** （0.041）	0.197*** （0.037）	0.163*** （0.028）	0.170*** （0.039）	0.165*** (0.038)	0.186*** (0.037)	0.193*** (0.038)	0.152*** （0.037）
Innovation					Yes			Yes
Smartcity						Yes		Yes

Autoinnicity							Yes	Yes
Control variable a term	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control variable quadratic term	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City Fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City FE Province - time FE	No	No	No	Yes	No	No	No	No
Observations	2470	2820	2820	2820	2820	2820	2820	2820

4.2.6. Resetting the DML Model

In an attempt to prevent the conclusions from being impacted by the bias of the DML model setting, this work continuously verifies the conclusions' robustness from the following perspectives. First of all, the machine learning algorithm is changed, and the random forest algorithm previously used for prediction is replaced with neural network and gradient lifting, and the possible influence of the prediction algorithm on the conclusion of this paper is explored. Secondly, this paper adjusts the sample segmentation ratio of the DML model from 1:4 to 1:2 and 1:7 respectively. Again, although this paper avoids the problem of two-way causality by controlling the lag of variables, and takes into account the factors that affect the IGG of the urban economy as far as possible, due to the limitation of data, it is inevitable that there are omitted variables and regression analysis is faced with endogenous problems. The method of instrumental variables can effectively alleviate endogenous problems. According to this, the paper takes Chernozhukov et al. (2018) as the basis for constructing a partial linear instrumental variable model for the DML, which is set up as follows.

$$IGG_{it+1} = \theta_1 Event_{it} + g\left(X_{it}\right) + U_{it} \tag{5}$$

$$Instrument_{it} = m\left(X_{it}\right) + V_{it} \tag{6}$$

where $Instrument_{it}$ is the instrumental variable for $Event_{it}$, here, this paper refers to Nunn and Qian (2014) and uses the interaction term between the urban topographic relief and the time trend term, which satisfies the homogeneity and correlation assumptions for instrumental variables.

Finally, the benchmark regression based on the DML model to construct a part of the linear analysis model, and the model form setting there is a certain degree of subjectivity, next, to investigate the influence of the model configuration on the findings of this study, this work uses the

DML model to build a more broad interactive model, used to analyze the main regression and auxiliary regression changes as follows:

$$IGG_{it+1} = g\left(Event_{it}, X_{it}\right) + U_{it} \tag{7}$$

$$Event_{it} = m\left(X_{it}\right) + V_{it} \tag{8}$$

The interactive model yielded the following estimated coefficients for the disposition effect:

$$\breve{\theta}_1 = E[g\left(Event_{it} = 1, X_{it}\right) - g\left(Event_{it} = 0, X_{it}\right)] \tag{9}$$

Table 4 displays the individual regression results. Observably, following the modification of the DML algorithm, changing the sample segmentation ratio, adding instrumental variables, and adopting the interactive model, the regression coefficient is still significantly positive, which indicates that the DML model setting does not affect the conclusion of this paper, and this confirms the robustness of the benchmark regression results once more.

Table 4

Dual machine learning robustness test.

Variables	（1） Replace machine learning models		（2） Change the sample segmentation ratio		（3） Instrumental variable	（4） Interactive model
	Nnet	*Gradboost*	*Kfolds*=3	*Kfolds*=8		
did	0.222**（0.099）	0.190***（0.034）	0.199***（0.035）	0.187***（0.040）	2.385***（0.836）	0.282***（0.032）
Control variable a term	Yes	Yes	Yes	Yes	Yes	Yes
Control variable quadratic term	Yes	Yes	Yes	Yes	Yes	Yes
Year Fe	Yes	Yes	Yes	Yes	Yes	Yes
City Fe	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2820	2820	2820	2820	2820	2820

4.3. Analysis of impact mechanisms

Based on the above analysis, it can be confirmed that the IGG of the urban economy can be supported by the TFCP policy. To further validate the mechanism of TFCP policy on urban economy IGG, this paper constructs the following intermediary model concerning the relevant literature (Namazi et al. 2016; Nemlioglu and Mallick 2020).

$$IGG_{it+1} = \theta_2 Event_{it} + g_1(X_{it}) + U_{1it}$$
$$E(U_{1it} \mid Event_{it}, X_{it}) = 0 \quad (10)$$

$$M_{it} = \theta_3 Event_{it} + g_2(X_{it}) + U_{2it}$$
$$E(U_{2it} \mid Event_{it}, X_{it}) = 0 \quad (11)$$

$$IGG_{it+1} = \lambda_0 Event_{it} + \lambda_1 M_{it} + g_3(X_{it}) + U_{3it}$$
$$E(U_{3it} \mid Event_{it}, X_{it}) = 0 \quad (12)$$

In the above equation, the M_{it} is the mediating variable, the mediating variables in this paper are technological progress (*Patent*), green innovation (*GPatent*), and digital financial inclusion (*DFII*) in order, and the remaining variables agree with the earlier paper. Among them, the natural logarithm of the total number of patent applications serves as a measure of technical advancement. Green innovation is measured using the natural logarithm of the number of green patent applications for each city. Furthermore, the Digital Financial Inclusion Index, developed jointly by Peking University's Digital Financial Research Center and the Ant Research Institute, represents the level of digital financial inclusion. Table 5 displays the individual regression results.

4.3.1. Technological progress

This research uses the natural logarithm of patent applications to evaluate urban technological development and performs regression analysis to examine the transmission mechanism that TFCP policy can affect the IGG of the urban economy by enhancing urban technological progress (Liu et al. 2024c). As can be seen in column (1) of Table 5, the regression coefficient of patent applications is extremely positive at the 1% level, demonstrating that the technological improvement brought about by the TFCP policy may significantly increase the level of IGG, and H2 is confirmed. Specifically, the reason why the enactment of the policy of TFCP can promote the IGG of urban economy through technological progress may be that science and technology finance can optimize the efficiency of resource allocation through government actions, foster the upgrading of industrial-technological level, and attract the gathering of scientific and technological talents, thus injecting capital into the science and technology in urban economies. It has aided in the advancement of technology, which has aided in the successful growth of the urban economy.

4.3.2. Green innovation

This paper employs the natural logarithm of green patent applications as a metric to quantify the extent of urban green innovation and proceeds to carry out regression analysis to examine whether the TFCP policy can enhance the level of urban green innovation, thereby influencing the transmission mechanism of IGG (Dian et al., 2024). The regression coefficient of TFCP policy is noticeably positive at the level of 1%, as can be shown in column (2) of Table 5, demonstrating that green innovation may support the IGG level and supporting H3. The reasons for the above results may mainly lie in the following aspects. First of all, science and technology and financial industries belong to the category of high knowledge-density industries, which have great attraction to the market and high return on investment. In a good development environment, they can have an advantageous effect on regional green innovation. Secondly, by optimizing the local financial environment through the TFCP policy, the financing challenges faced by innovators in the process of green innovation are lessened, which in turn encourages more small and medium-sized businesses to engage in green innovation activities (Jin et al. 2019). Finally, the increase and application of

green innovation provide technical support for the IGG of the urban economy, improve product productivity and improve product technology, and further promote the IGG of the urban economy.

4.3.3. Digital financial inclusion

To determine whether the TFCP's policy can advance the growth of digital inclusive finance and subsequently advance the level of IGG, this paper conducts regression analysis based on the China Digital Inclusive Finance Index and its sub-indexes measured by the Digital Finance Research Center of Peking University. The digital inclusive financial index and its sub-index can be seen to be significantly positive at the level of 1%, proving that TFCP policy has had a materially favorable influence on the IGG of the urban economy, confirming the transmission path of digital inclusive finance, and proving that H4 has been verified. The following factors help to explain this. First of all, by bringing together various policy preferences and inventing a method of technology financial investment, the adoption of the TFCP policy can encourage the growth of digital inclusive finance. At the same time, the policy can also attract external financial resources to flow into Hong Kong, promote the agglomeration of innovative resources (Yuan et al. 2019), and improve the financial service model in the pilot areas, hence supporting the growth of inclusive digital finance. In addition, from the perspective of the coefficient, the digital degree of digital inclusive finance is less than the breadth and depth of digital inclusive financial services, demonstrating that the depth and breadth of digitally inclusive financial services contribute more to easing the financing challenges faced by small and medium-sized businesses with a focus on technology (Cao et al. 2021). This promotes the expansion of urban financial business and then brings opportunities for the IGG.

Table 5

Results of the mediation effect test.

Variables	（1）	（2）	（3）	（4）	（5）	（6）
	Patent	*GPatent*	*DFII*	*Breadth*	*Depth*	*Digitization*
did	0.273***	0.362***	1.894***	1.866***	1.857***	1.732***
	（0.082）	（0.089）	（0.206）	（0.201）	（0.196）	（0.205）
Control variable a term	Yes	Yes	Yes	Yes	Yes	Yes
Control variable quadratic term	Yes	Yes	Yes	Yes	Yes	Yes
Year Fe	Yes	Yes	Yes	Yes	Yes	Yes
City Fe	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2820	2820	2820	2820	2820	2820

4.4 Heterogeneity analysis

4.4.1. Financial development

Different levels of financial development will result in variations in the amount of urban capital and the level of financial market regulation, which will in turn add to the IGG's heterogeneity. The standard used in this study is the average of the total annual deposits and loans made in the chosen cities, which are expressed as natural logarithms. It then divides the sample of cities into areas with high and low levels of financial development and performs the regression to examine the heterogeneity of the TFCP policy on the IGG of the urban economy under different levels of financial development. Table 6's Columns (1) and (2) present the results of the regression.

The regression findings show that the TFCP policy strategy may successfully promote the IGG of the urban economy regardless of the level of financial development of the region. However, in contrast to cities that have lower financial development levels, it is important to note that technology finance in cities that have higher financial development levels has a more pronounced encouraging effect on the IGG of urban economics. The reason for this may be that, on the one hand, the financial market of cities with a higher level of financial development is more perfect and standardized, and the optimization of resource allocation and access to high-quality assets by the developed financial market can realize the improvement of capital flow and utilization efficiency. In cities with less developed financial systems, due to the lack of economic strength and talent attraction, it is difficult to rely solely on the government's public finance to provide favorable support for innovative activities, which leads to slow industrial upgrading, and the effect of IGG of the urban economy is difficult to be highlighted. On the other hand, for cities with a higher level of financial development, the financial institutions in the region have a greater advantage in terms of quantity and quality, which can provide more adequate financial security and diversified sources of funds for the IGG of urban economy, and effectively alleviate the pressure on the city's public finances.

4.4.2. Geographic location

Under the realistic background, due to the existence of geographical location, historical conditions, policy environment, and other factors, the impact of TFCP policy on the economic IGG of cities in different regions will be different. To investigate the heterogeneity of policy effects caused by different geographical locations, according to the areas to which different cities belong, the sample cities are sorted into three groups including eastern, central, and western, and group regression is performed. Table 6 shows the individual regression results in columns (3) through (5).

According to the regression results, the regression coefficients of TFCP policy on the economic IGG of eastern and central cities are considerably positive at the 1% level, with the influence on eastern cities being bigger than that of central cities. The reason may lie in that, on the one hand, the eastern region has convenient transportation and a good economic foundation, so the TFCP policy can make use of the location advantages of the eastern region, through perfect supporting facilities to enhance the economic development effect of science and technology finance (Lu et al. 2023). On the other hand, the first batch of projects of TFCP integration is mainly concentrated in the eastern region, so the eastern region has a longer history of science and technology finance development, which makes the operation experience and institutional environment more perfect. In addition, the regression results show that the policy effect of the TFCP project is not significant in the western region, which may be because the foundation of economic development in the western region is weak. for a long time, it has been dominated by resource and labor-intensive industries, weak scientific and technological innovation ability, and a serious brain drain, which may greatly reduce the policy effect of TFCP on the IGG of urban economy. In conclusion, the IGG of the urban economy in the eastern region is more positively impacted by the TFCP policy.

4.4.3. Political status

In addition to geographic heterogeneity, China's cities also have political status differences, which is mainly manifested in the fact that, for prefecture-level cities, provincial capital cities and sub-provincial cities have natural advantages in access to political resources and other aspects, as well as the more adequate financial capacity to implement relevant national policies. Therefore, this article divides province capital cities and sub-provincial cities into cities with political status and divides other cities into general cities to examine whether the influence of the TFCP policy on the IGG of urban economy differs in different cities with varied political status. Columns (6)-(7) of Table 6 show the specific regression results.

The regression results show that the policy effect of TFCP on the economic IGG of both political-status cities and general cities is significantly positive, but the estimated coefficients are larger for political-status cities compared with general cities, that is, the impact of TFCP policy on the economic IGG of political status cities is more substantial. This may be because governments in political-status cities are more willing and able to spend a lot of money and resources to support innovation in science and technology as well as to enhance the quality of economic growth by maximizing resource allocation and encouraging the modernization of industrial structure to take advantage of the benefits of the talent concentration and economic agglomeration effect (Zhao and Xu 2023). In addition, cities with political status have policy advantages in terms of policy pilots and other aspects, higher acceptance of emerging policies, and more reasonable resource allocation, thus enabling scientific and technological talents to have a better development platform. The above external conditions optimize the development environment of TFCP, thus making the promotion effect of TFCP policy on the political status of cities more obvious.

4.4.4. Industrial base

The strategy of prioritizing heavy industry, which was vigorously pursued during China's planned economy, is a key factor in the disparate urban economic growth, as the transitional tilt of heavy industry distorts the industrial structure, while the capital-intensive nature of the heavy industry sector reduces the absorption of rural labor, thus widening the economic development gap among cities. Therefore, to further investigate whether the TFCP policy can promote the transformation and upgrading of old industrial bases, and thus promote the IGG, this paper splits the sample of cities into old industrial bases (*excluding prefectural level and above cities involving only some county jurisdictions*) and non-old industrial bases, and conducts a subgroup regression analysis. Table 6 shows the results in columns (8)-(9).

As can be observed, the TFCP policy's regression coefficient to non-industrial basis cities is considerably positive at the level of 1%, but it is not significant for the old industrial base cities. This demonstrates that while the TFCP program may be able to support the economic IGG of non-industrial base towns, its effects on the economic IGG of the older industrial base cities are less clear. The reason is that due to the previous weak industrial base, the non-industrial base may turn to the emerging industries, the TFCP policy is more easily accepted by the industrial departments in the region, and the industrial structure transformation and upgrading ability of the non-industrial base is stronger. As a result, the boosting effect on the urban economy IGG is more visible. Furthermore, the cities associated with the old industrial base are dominated by the heavy industry sector, and the region's characteristics of high emissions and high energy consumption are obvious, stifling the transformation and upgrading of the local cities' industrial structures and impeding IGG of the urban economy.

Table 6

Heterogeneity analysis.

Variables	(1) High financial level	(2) Low financial level	(3) Eastern city	(4) Central city	(5) Western cities	(6) Political status city	(7) General city	(8) Old industrial bases	(9) Non-industrial base
did	0.232*** (0.042)	0.117** (0.056)	0.228*** (0.058)	0.217*** (0.061)	0.048 (0.054)	0.312*** (0.065)	0.090** (0.045)	0.095 (0.066)	0.251*** (0.049)
Control variable a term	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Control variable quadratic term	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year Fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City Fe	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1200	1620	990	1000	830	360	2460	940	1880

5. Tests for spatial effects

Promoting the implementation of the policy of TFCP is a favorable means for the government to step in and influence the urban economy's IGG, which can affect the economic IGG of the pilot and non-pilot cities by affecting the flow of innovative resources, knowledge and technology spillover and policy innovation diffusion, and then derives two competitive viewpoints, namely siphon theory with emphasis on siphon effect and spillover theory with emphasis on spillover effect. This work offers the spatial econometric analysis approach for empirical tests to validate the existence of the aforementioned two effects.

5.1. Constructing the spatial weight matrix

Spatial weight matrix is a key component of spatial econometric research. The geographic adjacency matrix, economic geography matrix, and geographical inverse distance square matrix make up the spatial weight matrix frequently employed in the field of spatial econometrics. Intending to conduct the spatial effect of the TFCP policy in a more three-dimensional way, this paper uses the 0-1 adjacency matrix to examine the comprehensive impact of the enactment of the TFCP policy on the IGG of the economy of non-pilot regions.

Referring to Yuan et al. (2019) and Liu et al. (2022b), the spatial adjacency matrix is constructed with the following formula:

$$W_{ij} = \begin{cases} 0, When \quad city \quad i \quad and \quad city \quad j \quad are \quad not \quad adjacent \\ 1, When \quad city \quad i \quad is \quad adjacent \quad to \quad city \quad j \end{cases} \tag{13}$$

5.2. Spatial DID modeling and decomposition of policy effects

The spatial double difference model consists of spatial measurement and double difference model, and in the existing research, most models combining the spatial measurement model and double difference are the independent variable spatial lag model (*SLX*) and spatial Durbin error model (*SDEM*). To verify the scientific validity of spatial econometric model selection, this study screens the optimal model using the LM test and the Wald test and chooses the usage of a fixed/random effect model using the Hausman test. Based on the results of the above treatments and concerning Elhorst (2014) and Lu et al. (2023), the SLM model and SDEM model are used to jointly explore the spatial effects of policies. In addition, this paper refers to Chagas et al. (2016) to decompose the spatial matrix to eliminate the estimation error due to regional correlation, while further considering the use of differentiation methods to analyze spatial data with local spatial interactions to simulate the effect of experimental groups on adjacent non-experimental groups. This work decomposes the spatial matrix W into the following form according to the methodology discussed above:

$$W = W_{T,T} + W_{T,NT} + W_{NT,T} + W_{NT,NT} \tag{14}$$

where W_{ij} denotes the neighborhood effect of the region on region i, i,j = T (*treated*) or NT (*untreated*).

$$\begin{cases} W_{T,T} = D_t * W * D_t \\ W_{T,NT} = D_t * W * D_t^C \\ W_{NT,T} = D_t^C * W * D_t \\ W_{NT,NT} = D_t^C * W * D_t^C \end{cases} \tag{15}$$

where did is on the main diagonal and the rest of the positions are 0, the formula D_t=*diag (did)* is an *n*n* matrix, and D_T^C =*diag*(l_n-*did*). l_n is a vector of 1's. The fact that $W_{T,NT}$ and $W_{NT,NT}$ are 0 after the decomposition, therefore, the only spillover effects that need to be taken into account are those that occur within the experimental group and those that occur when the experimental group interacts with the non-experimental group.

5.3. Analysis of regression results

Table 7 displays the results of the model regression. The findings illustrate that, regardless of the SLM model or SDEM model, the influence coefficient of TFCP policy execution on the IGG of pilot regions is highly positive at the level of 1%. This finding is in line with the findings of the benchmark regression study, and both results support the positive impact of the TFCP policy on the IGG of pilot cities. Moreover, it is also worth noting that the sign of $W_{T,T}D$ is consistent with the direct effect but less significant, which shows that the spatial spillover effect of the TFCP policy within the pilot region cities is weak, i.e., the interaction between the pilot regions is not obvious. However, the sign of $W_{NT,T}D$ is opposite to the direct effect and significantly negative under the SLM model. This shows that there is a spatial transfer of inclusive green development between pilot cities and non-pilot cities. The reason may be that under the impact of TFCP policy, pilot cities can rely on policy advantages to gather capital and knowledge resources, creating opportunities for further economic development (Huang et al. 2022). However, due to the lack of policy advantages, non-pilot cities lead to the outflow of resources such as talent and technology, which makes the IGG pilot cities and non-pilot cities show a trend of growth and decline (Bian et al. 2024). Generally speaking, the above analysis confirms the existence of the "siphon effect". In the initial stage of the TFCP policy, it brings about a siphon effect on neighboring cities' growth, attracting resources from

non-pilot areas to flow into the pilot areas, and then restraining the further improvement of the IGG level of non-pilot cities as a whole, thus verifying H5b.

Table 7

Spatial spillover effects test.

Variables	SLM	SDEM
	IGG	IGG
did	0.106***	0.010***
	(0.035)	(0.018)
$W_{T,T}D$	0.009	0.007
	(0.014)	(0.009)
$W_{NT,T}D$	-0.021***	-0.005
	(0.006)	(0.003)
R^2	0.9413	0.6179
log-likelihood		747.2509
Control variables	Yes	Yes
Year FE	Yes	Yes
City FE	Yes	Yes
Observations	2820	2820

6. Conclusions and policy recommendations

This paper aims to construct a comprehensive analytical framework, regards the implementation of TFCP policy as a quasi-natural experiment, and calculates the IGG level of 282 cities in China from 2010 to 2020 from the four dimensions of economic growth, income distribution, welfare benefits and environmental pollution reduction, explores the effect of TFCP policy on the improvement of urban IGG level, and reveals its internal mechanism. The feasibility study of the policy is expanded and supplemented. The results of the study are summarized as follows: Firstly, the cities' IGG levels are greatly improved by the use of TFCP policy, particularly when it comes to fostering economic growth and income distribution. Numerous robustness tests have additionally verified the validity and robustness of this conclusion. Secondly, the mechanism and path of technological progress, green innovation and the development of digital inclusive finance are verified through mechanism analysis. The TFCP policy's adoption can quicken the flow of funding to pilot regions. Meanwhile, relying on policy advantages, pilot areas gather a large number of capital and talent. An increasing number of green patents offer strong network and technical assistance for the growth of urban IGG. In addition, the heterogeneity analysis found that, compared with cities with low financial development levels, the positive impact of policies in cities with high financial development levels is more significant, and the heterogeneity of policies in cities with different geographical locations is also present, and it is especially conducive to the transformation of high-quality economic development in cities with political status and non-industrial base cities. Finally, the further spatial effect test shows that the policy effect of TFCP mainly benefits the pilot areas. Through its political advantages, TFCP gathers capital and technological advantages for the pilot areas, thus promoting the IGG development of the pilot cities. However, for the non-pilot areas, TFCP policy plays a certain siphon effect, crowding out the economic resources in the non-pilot areas, and preventing IGG from developing in this region.

Based on the above research conclusions, several policy implications related to the empirical results are formulated:

First, the theoretical model and practical experience show that the execution of TFCP policy can improve the level of scientific and technological innovation in pilot cities and ease their financing constraints, which is crucial for accelerating urban economic development and green transformation. Consequently, in the future for a long time, the central government can properly adjust the policy, and prolong the effect policy, meanwhile, the government can also actively summarize the current pilot experience, appropriately expand the scope of policy, accelerate the formation of a national comprehensive science and technology and financial system, for the future urban economic transformation and modernization to create space. Second, Pilot cities should place a high value on the beneficial role that TFCP policy plays in fostering innovative technology and the digital economy. They should also actively work to improve the infrastructure and service systems that support these technologies, direct the flow of capital and scientific and technological resources in a logical and orderly manner, foster a high-caliber business environment, and offer strong support for the rapid development of advantageous elements. At the same time, enterprises in the pilot area should keenly capture the innovation effect and allocation effect brought by TFCP policy, and actively make use of policy dividends to promote the upgrading and green transformation of production structure and mode, so as to meet the development needs of the new era and achieve sustainable development. Furthermore, governments should be acutely aware of the diverse implications of various urban characteristics, and devise correct and differentiated development strategies to effectively react to and deal with policy impacts. Based on the heterogeneity of various cities in terms of financial development level, geographical location, political status, and industrial base, Local governments should accurately grasp the unique location characteristics of each city and implement appropriate macro-control strategies according to local conditions. At the same time, it is also necessary to make full use of the advantageous resources of each city to guide the rational landing and implementation of policies more scientifically, to maximize the effect of policies, ensure that policy dividends can benefit all kinds of economies, and promote the balanced and sustainable development of urban economy. Fourth, governments at all levels should strengthen exchanges and cooperation among cities and jointly build a diversified and integrated economic development circle. Each city is an important part of economic development, with interwoven cooperation and connections. Although at the initial stage of the policy, the TFCP's policy influence only benefits pilot cities, with the further development of the policy, its policy influence will expand to a wider range of cities, giving full play to its synergies, and thus promoting the sound development of the entire economy.

Although this study confirmed the positive effect of TFCP policy on urban IGG with a series of empirical results, it supplemented and improved the current literature. However, there are some limitations to this study. First of all, the intermediary mechanism of TFCP policy on urban IGG is not comprehensive. In addition to the three intermediary paths mentioned in the paper, government subsidies, public attention, and mass entrepreneurship all have potential mechanisms of action. Due to data limitations, space structure, and other factors, it is difficult to exhaust all influencing factors in the study. Secondly, the implementation of the policy is complicated, and its efficient effect is a combination of various factors such as time, geographical location, and people. The positive effect of a policy in one place does not mean that the policy is suitable for the development of another place. Therefore, not all cities are suitable for the implementation of TFCP policy. In addition, due

to the impact of the novel coronavirus epidemic, the 2020 data samples may have biases, which means there exists a lot of unexplored territory in the temporal dimension that requires careful consideration. Based on the above limitations, future studies can supplement the multiple paths that TFCP policy affects economic development from a more multidimensional perspective and based on more accurate data, comprehensively view the value and significance of TFCP policy.

Availability of data and material

Data and material will be made available on reasonable request.

Authors' contributions

Guoyong Wu: Resources, Visualization, Validation.

Mengmin Sun: Conceptualization, Methodology, Writing-original draft.

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Declarations

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Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

List of abbreviations

1. IGG is the abbreviation of inclusive green growth.
2. TFCP is the abbreviation of technological finance cooperation pilot.
3. DML is the abbreviation of dual machine learning.
4. DID is the abbreviation of difference in difference

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