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Innovative policy synergies driving inclusive green growth: causal inference based on double machine learning

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Inclusive green growth aims to achieve multi-dimensional coordinated development of the economy, society and the environment. It is worth delving into how integrated innovation policies can systematically drive this goal. Utilizing a double machine learning model and panel data from 266 prefecture-level cities spanning 2006–2022, this study investigates the indirect transmission methods and impact effects of the “dual pilot” program—combining innovative city and national independent innovation demonstration zone initiatives—on inclusive green growth. The analysis is grounded in the Technology-Organization-Environment framework and investigates the policy’s heterogeneous effects across urban dimensions of location, characteristics, and scale, consistent with TOE theory. The results show that: 1. The “dual pilot” policy greatly encourages inclusive green growth and has a synergistic effect larger than the sum of its parts; this conclusion is supported by a number of reliability tests; 2. The mechanism tests indicate that the “dual pilot” policy can indirectly promote inclusive green growth by increasing R&D investment and facilitating the diffusion of technological innovation at the technological level, advancing the structure of human capital and upgrading the industrial structure at the organizational level, and strengthening both formal and informal environmental regulations at the environmental level; 3. Heterogeneity analysis shows that the policy’s positive impact on inclusive green growth is more pronounced in eastern cities, non-resource-based cities, and major-sized cities. This research broadens the perspective on how innovative city and national independent innovation demonstration zone development contributes to inclusive green growth, providing empirical evidence and practical insights for promoting such growth.

KEYWORDS
double machine learning, inclusive green growth, innovative city pilot, national independent innovation demonstration zone, policy effect

1 Introduction

Faced with global challenges such as shortages of resources, environmental degradation, and intensifying social inequality, the traditional extensive economic growth model reliant on environmental resource exploitation has become increasingly unsustainable. In this context, green growth oriented toward ecological and environmental protection (Zhou, 2020) and inclusive growth, which emphasizes equal opportunities and shared benefits during economic expansion, Khan et al. (2025) have been widely regarded as new pathways for implementing sustainable development (Ofori et al., 2023). Inclusive green growth (IGG), which integrates the core principles of both concepts, has been widely recognized as a key indicator for measuring national development progress at this stage. Given this consensus, countries have successively incorporated inclusive green growth into their development strategies, actively exploring new sustainable development paths suited to their national conditions. Examples include the U.S. *Inflation Reduction Act*, which allocates $459.5 billion in funding for environmental justice, and the European Green Deal, which aims to address social inequality through mechanisms such as the Just Transition Fund.

China is essential to reaching global IGG targets because it is the largest developing nation in the world and a significant carbon emitter. While achieving rapid economic growth, China also faces dual pressures of balancing development with ecological protection and improving both the quality of growth and social equity, making it a highly valuable case study. According to the *Emerging Economies Carbon Dioxide Emissions Report 2024* recently released by the China Emission Accounts and Datasets (CEADs), China's GDP surged from 40 trillion yuan in 2010 to 110 trillion yuan in 2021. However, carbon emissions from fossil energy consumption also increased from 7357.7 million tons to 9665.4 million tons during the same period, representing a rise of 31.4%. The concurrent increase in overall carbon emissions and economic growth highlights the ecological constraints of the traditional growth model and underscores the urgent need to transition toward inclusive green growth. To this end, in the *Proposal of the Central Committee of the Communist Party of China on Formulating the Fourteenth Five-Year Plan for National Economic and Social Development*, China explicitly identifies the coordinated advancement of "carbon reduction, pollution control, green expansion, and growth" as a core policy direction, committing to building a development framework that integrates economic, social, and ecological benefits. Nevertheless, China is still in a critical stage of sustainable development, facing multiple challenges such as weakening growth momentum, prominent environmental pressures, social inequality, and insufficient technological innovation efficiency. Against this backdrop, how to effectively promote IGG is not only a core issue to be addressed for China's pursuit of high-quality development but also offers valuable insights for other developing countries facing similar transitional challenges, thereby carrying both academic significance and practical value.

In recent years, the positive intrinsic connection between innovation incentives and IGG (Wang et al., 2023) has garnered widespread academic attention. Technological progress driven by innovation can not only enhance social productivity and output but also reduce the dependence of economic growth on environmental resources while improving people's welfare and expanding the sharing of development benefits (Jia L. et al., 2023). Regarding the mechanisms through which innovation incentive policies affect IGG, existing research has provided some empirical support across multiple policy areas. Serbanica and Constantin (2017) pointed out that smart specialization innovation policies, grounded in local comparative advantages, can effectively support eco-innovation in Central and Eastern European countries, thereby promoting the achievement of IGG. Research by Ren et al. (2022) indicates that innovation policies in the information and communication field can provide momentum for IGG development by fostering the agglomeration of the digital economy. Furthermore, innovation policies in the financial sector have also been proven to have positive effects. For instance, innovations in financial instruments such as green credit can improve environmental quality and support economic growth (Guru and Yadav, 2019; Wang et al., 2021).

However, given the environmental negative externalities characteristic of IGG, although innovation policy interventions can guide the actions of others of innovation entities and the direction of factor allocation (Yang and Xue, 2024), in order to achieve Pareto optimality, a single policy tool will always have constraints (Su et al., 2022). This necessitates the synergistic integration of innovation policy tools to strengthen the driving effect of innovation on IGG. In the Chinese context, the innovative city pilot (ICP) policy employs city-level institutional experimentation to amplify the external economies of green knowledge and technology through shared platforms, risk compensation funds, and open green application scenarios. Yet, it has not sufficiently addressed the channel for industrial-scale commercialization. Conversely, the national independent innovation demonstration zone (NIIDZ) policy leverages park-level industrial agglomeration and full-cycle green financial instruments to rapidly dilute the commercialization costs of environmentally friendly technology. The combined "dual pilot" policy innovatively integrates the internalization of positive externalities from front-end knowledge creation with the economies of scale from back-end industrialization. It complements the urban innovation incentive model with the park-based industrial acceleration model, thereby overcoming the inherent limitations of singular policy tools and emerging as a key institutional vehicle with the potential to unleash the potential of IGG.

While existing studies have extensively explored the impacts of various single innovation policies on IGG, laying a theoretical foundation for identifying policy effects, there remains a lack of in-depth investigation into the potential synergistic or combined effects of innovation policy mixes. In terms of research methodology, current evaluations of cluster policies predominantly rely on the traditional Difference-in-Differences (DID) method. Such approaches still face challenges in addressing issues such as uncertainty in confounding factors' functional form, the curse of dimensionality in high-dimensional data, and regularization bias (Han et al., 2025). Notably, the double machine learning method, which has emerged in recent years in the realm of causal inference, can effectively handle high-dimensional confounders and capture nonlinear causal mechanisms. This offers new potential for identifying the effects of complex policies such as the innovation-driven "dual pilot" policy. However, its application in relevant policy evaluations has not yet received sufficient attention. Building on this, this essay is centered on addressing the following questions: What specific impact does the innovation-driven "dual pilot" policy, composed of the ICP and NIIDZ policies, have on enhancing IGG? Does the "dual pilot" policy generate a "1+1>2" synergistic effect? Furthermore, if the impact is positive, what are the underlying mechanisms? Does this effect vary depending on a city's technological foundation, industrial organizational structure, and institutional environment? To answer these questions, the impact mechanisms and varied consequences of the innovation-driven "dual pilot" policy on IGG are thoroughly investigated in this research using the double machine learning approach. This study aims to provide a reliable basis for optimizing policy design and assisting other developing countries in enhancing their IGG levels, while also offering an original perspective to facilitate the deepened application of the strategy for innovation-driven development.

Consequently, this paper's marginal contributions are as follows: First, in terms of research perspective, the article evaluates the consequences of the "dual pilot" policy, which is driven by innovation, from the angle of policy synergy, providing a certain supplement to the study of innovation policy mix effects. Second, at the theoretical level, it examines the linkage between the innovation-driven "dual pilot" policy and IGG. Grounded in the TOE theory, it innovatively explores the manner in which IGG is impacted by the innovation-driven "dual pilot" strategy, thereby broadening the theoretical boundaries. Finally, in the analysis of effects, this study examines the various expressions of the policy effects from multiple dimensions, including technological foundation, industrial organizational structure, and institutional environment. This offers clearer directions for policy recommendations to the Chinese government and even other developing countries in effectively promoting sustainable development.

Following the introduction, this is how the rest of the paper is structured. The literature review is presented in the second section, summarizing relevant research on the ICP policy, the NIIDZ policy, and IGG. The third section explores the research hypothesis and provides more details on the study's institutional background. The fourth section introduces the model construction, including the model specification, variable selection, data sources, and descriptive statistics. The fifth section comprises the empirical tests conducted to verify the theoretical hypotheses. The sixth section discusses the universality, heterogeneity, and indirect effects on IGG of the "dual pilot" policy pushed by innovation. Finally, the study's limits and future potential are discussed, along with the research findings and policy implications.

2 Literature review

2.1 Evaluation of single innovation policy effects: the innovative city pilot policy and the national independent innovation demonstration zone policy

With the deepening implementation of the ICP and the NIIDZ, academic circles have extensively studied the multifaceted policy effectiveness of these two types of innovation policies.

Existing research on the ICP indicates that the construction of innovative cities follows an incremental exploratory path. As a key government initiative to support innovation, the pilot policy has effectively promoted the agglomeration of innovation factors (Zhao and Fang, 2023) and significantly enhanced urban innovation capabilities. Studies have confirmed that this policy generates positive economic effects on enterprise innovation (Li et al., 2020), drives the transformation and application of technological innovation achievements (Yang and Li, 2020), and contributes to China's economy's green transition (Jia F. et al., 2023).

Existing research on the NIIDZ shows that it relies on the important platform of national high-tech zones, interconnecting existing parks into networks. Using standard industrial policy instruments like tax breaks, government subsidies, and low-interest loans, it enhances the independent innovation capacity and radiating influence of national high-tech zones (Zhang et al., 2020). Studies have confirmed that this policy can leverage agglomeration effects (Yan and Yan, 2019), attracting a large concentration of innovation factors and high-quality resources. It promotes the flow and sharing of innovation factors among enterprises (Guo et al., 2021), reduces transaction costs, and drives regional collaborative innovation and economic growth (Tang et al., 2026). Furthermore, by leveraging the first-mover advantages of institutional innovation and the market selection mechanism of survival of the fittest, it significantly improves the R&D performance of high-tech zones (Zhang et al., 2020).

2.2 Research on inclusive green growth

IGG is a sustainable development approach encompassing economic, social, and environmental dimensions, which has been widely discussed in academia. This paper reviews the relevant literature on IGG, primarily focusing on two aspects: conceptual connotations and influencing factors.

On the one hand, IGG is an integrated concept derived from inclusive growth and green growth. In 2005, the idea of "green growth" was initially put up at the United Nations Economic and Social Commission for Asia and the Pacific's (UNESCAP) Environment and Development Ministerial Meeting, defining it as a low-carbon and environmentally friendly green development model. The term "inclusive growth" was originally used by the Asian Development Bank in 2007, viewing it as an economic growth model advocating equal opportunities. The concept of IGG was initially highlighted by the World Bank at the "Rio+20" Summit in 2012, indicating that IGG is a synthesized concept combining the essential characteristics of inclusivity and green development. Subsequently, numerous scholars have provided various conceptual definitions and interpretations of IGG from different perspectives. For instance, Zhang (2014), from the three dimensions of economy, society, and environment, argued that IGG places greater emphasis on the role of "people" in environmental, economic, and social development, particularly in terms of inclusive support and protection for disadvantaged groups such as the poor. Berkhout et al. (2018), considering social equity and equal opportunities, defined IGG as a form of pro-poor growth. Li and Dong (2021) elaborated on the connotations of IGG from multiple dimensions—innovation, coordination, green development, and sharing—asserting that IGG can effectively measure the level of high-quality economic development.

On the other hand, existing research explores the factors promoting IGG from three levels: technology, organization, and environment. From a technological perspective, the increase in digital infrastructure (Li et al., 2023) can facilitate regional green development by promoting low-carbon transformation in enterprise production methods, encouraging green and low-carbon shifts in residents' lifestyles, and innovating government environmental regulatory approaches. Digitalization can effectively drive IGG through cost effects and innovation effects (Wang et al., 2025a). From an organizational perspective, the expansion of resident employment scale (Zhang and Luo, 2024) not only provides stable economic sources for more people but also encourages broader participation in economic activities, enabling more individuals to share the benefits of economic growth, thereby promoting regional IGG. From an environmental perspective, the development of industrial intelligence (Wu et al., 2024) offers more service job opportunities for low-skilled groups, reflecting characteristics of inclusive growth. Additionally, in the long term, the development of artificial intelligence contributes to the reduction, recycling, and harmless treatment of industrial waste throughout production processes, guiding the transformation of industrial production methods toward digitalization and green development, thereby embodying green development characteristics (Wang et al., 2025a).

2.3 Research on the coordinated effects of innovation-driven policies

The strategic integration of policy tools has attracted increased scholarly interest due to the diverse and complex nature of innovation-driven policies. However, the influence of "innovation-driven policy mixes on IGG" has not yet been thoroughly examined in systematic studies, and the nature and extent of possible synergistic effects have not been sufficiently described. Therefore, this paper explores the issue from the more general perspective of the coordinated effects of innovation-driven policies, providing a foundation for subsequent research.

Existing academic studies primarily concentrate on the synergistic effects of innovation policy mixes within different technological domains, such as innovative medical technologies (Aminullah and Erman, 2021), intelligent transportation technologies (Khatoon et al., 2024), and renewable energy technologies (Luo et al., 2024). Furthermore, some research indicates that the integrated application of multiple innovation-driven instruments can reduce environmental pollution and enhance public wellbeing. For instance, Ladu et al. (2020) demonstrated that combining sustainability policies with innovation policies can assist in transitioning fossil-based societies towards a bio-economy grounded in sustainable biological resources. Kivimaa et al. (2023) showed that a series of transformative innovation policies, coupled with supportive measures in Finland, contribute to resilient economic growth and secure development.

By synthesizing the aforementioned research, several areas for improvement can be identified: First, scholarly investigation into IGG from the perspective of innovation-driven policy combinations remains limited. A substantial body of work focuses on evaluating single innovation policies, overlooking the complementarity and coherence among different policy instruments. Second, although many researchers recognize the importance of innovation-driven policies for economic, environmental, and social equity outcomes, existing analyses have not sufficiently delved into their underlying mechanisms. Moreover, numerous studies adopt a fragmented approach, attributing effects to either technological, organizational, or environmental factors in isolation, lacking an integrative theoretical framework to systematically analyze how these factors jointly drive IGG. In particular, there is a scarcity of comprehensive analyses based on the TOE framework examining the factors that promote such innovative progress. Finally, in the comprehensive assessment of the effectiveness of the "dual pilot" policy (combining the ICP and NIIDZ), there is an absence of differentiated analysis considering variations in urban technological foundations, industrial organizational structures, and institutional environments. This gap makes it more difficult to give governments and pertinent departments the theoretical and scientific proof they need to adopt precise and customized policies.

3 Theoretical analysis and research hypotheses

3.1 Institutional background

To foster the robust emergence of IGG, the state has sequentially implemented the ICP and the NIIDZ policy. On one hand, since the strategic objective of creating a nation focused on innovation was put forth in the 2005 *National Medium- and Long-Term Science and Technology Development Plan (2006–2020)*, China has gradually advanced its ICP work. In 2008, Shenzhen was approved as the first pilot city for this policy, adopting an incremental approach characterized by "pioneering trials, accumulating experience, and gradual advancement." The National Development and Reform Commission gave 16 cities permission in 2010, including Qingdao, Dalian and Xiamen, to initiate pilot programs. Subsequently, the list of pilot cities has continued to expand in response to developmental needs. By 2022, the number of national innovative city pilots had reached 101, achieving comprehensive coverage across eastern, central, and western regions. On the other hand, since Beijing Zhongguancun became the first NIIDZ in 2009, the State Council has successively approved 21 NIIDZs, encompassing 56 cities and 62 national high-tech zones across the country. By pioneering policy experiments and leveraging park-level industrial agglomeration alongside full-cycle green finance, these demonstration zones significantly reduce the commercialization costs of green technologies. They promote green technology innovation and institutional reforms, thereby providing crucial support for nurturing IGG. Against the macro background of concurrently pursuing the "Dual Carbon" strategy and high-quality development, these pilot cities continuously strengthen green technology R&D, achievement transformation, and industrial implementation based on their local industrial foundations, therefore encouraging the growth of IGG. The development processes of the ICP and the NIIDZ policy are illustrated in Figure 1.

The ICP and the NIIDZ policy serve as key drivers for promoting IGG, with their implementation timelines closely aligned and their geographic coverage overlapping. This study treats the "dual pilot" scenario, where a city simultaneously implements both policies, as a quasi-natural experiment to investigate whether their combined application can synergistically enhance the level of IGG.

3.2 Theoretical analysis

3.2.1 Direct influence mechanism and research hypothesis

According to institutional theory, policy implementation is a crucial component that links the goals of policies with their actual

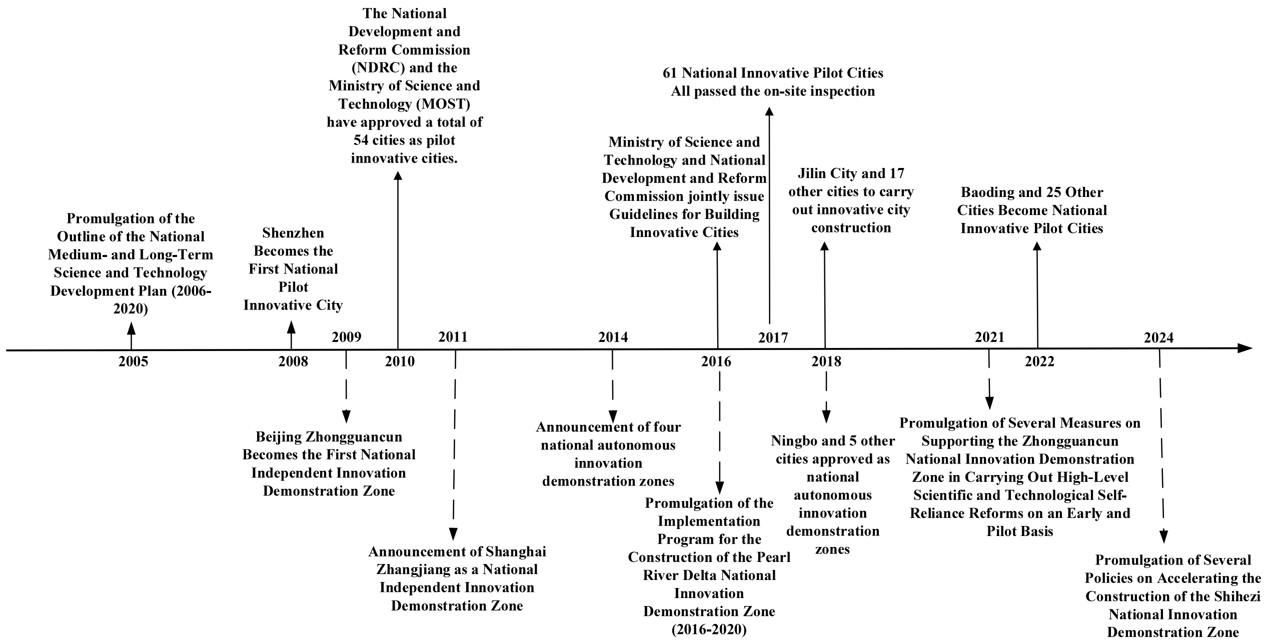

FIGURE 1
Policy development history.

results. As a super-sized nation, China's multi-level central-local implementation chain renders its policy execution context more complex and dynamic (Yang, 2024). This leads to temporal fluctuations and regional variations in local government policy implementation, thereby causing differentiated policy effects.

Within this institutional context, the synergistic interaction between the ICP and NIIDZ holds the potential to enhance policy effectiveness through institutional coupling, thereby promoting the development of IGG. As a source of innovation and an institutionally empowered innovation vehicle, the ICP can provide substantial human capital and R&D investment for low-carbon innovation through a series of innovation resource-oriented strategies, such as building innovation platforms, providing research funding subsidies, and offering talent housing guarantees (Li and Zhao, 2024). This facilitates the output of green innovation technologies. By fostering an innovative institutional environment, the pilot promotes organic interaction among universities, research institutes, and enterprises within the innovation value chain. Through constructing open innovation networks and empowering innovation infrastructure development, it accelerates the high-quality transformation of innovation outcomes into IGG (Wang et al., 2025). The NIIDZ, through deepening institutional innovations in key areas such as incentive-based equity systems, tax mechanism reforms, and government efficiency improvements, builds a flexible institutional system that supports innovation in technology in small and medium-sized businesses. This significantly enhances corporate innovation motivation and improves R&D performance (Lan et al., 2022). Concurrently, as a frontier for future industries, it accelerates the development of IGG by leveraging innovation resource agglomeration and the commercialization of scientific and technological breakthroughs. Its developmental practices exemplify the characteristics of Chinese modernization and accelerate the realization of green innovation value (Ma and Kang, 2024).

Compared to single-pilot regions for innovation-driven policies, "dual pilot" cities possess more favorable conditions for supporting IGG. By integrating policy resources and coordinating institutional efforts, the "dual pilot" approach can more effectively reduce transaction costs for innovation actors. It fosters an efficient innovation ecosystem that accelerates the agglomeration of high-level talent, the commercialization of cutting-edge technologies, and the influx of venture capital. First, "dual pilot" cities are more attractive in talent policies (Xiao and Pan, 2026), optimizing the development environment to attract top-tier talent and teams, thereby stimulating innovation vitality and solidifying the talent foundation. Second, "dual pilot" cities demonstrate greater flexibility and innovation in financial policies (Huang et al., 2023). By utilizing innovative financial instruments and services to broaden financing channels, they can alleviate financing constraints and provide robust financial support for SMEs and innovative projects. Finally, "dual pilot" cities can amplify policy aggregation effects, promoting resource integration and ecosystem optimization, enhancing innovation efficiency, and providing broader space and opportunities for IGG, demonstrating a powerful driving force.

In summary, both the ICP and the NIIDZ can promote IGG. Moreover, the impact of "dual pilot" cities is perhaps more noticeable than that of single-pilot cities.

In light of this, the following Hypotheses 1 and 2 are put out in this paper:

Hypothesis 1: An increase in IGG can be directly and synergistically encouraged by the "dual pilot" policy.

Hypothesis 2: The "dual pilot" approach is more able to promote IGG in a synergistic way than a single pilot program.

3.2.2 Indirect influence mechanism and research hypothesis

The TOE theory posits that technological innovation decisions are the result of the dynamic interaction among three categories of factors: technological conditions, organizational characteristics, and environmental context. This aligns with the policy application scenario of the "dual pilot" policy, which is driven by innovation. Consequently, this paper applies the TOE theory to analyze the driving mechanisms through which the innovation-driven "dual pilot" policy influences IGG, aiming to explore how various elements within the technological, organizational, and environmental dimensions synergistically interact to collectively promote IGG.

Firstly, the technological dimension focuses on the applicability, compatibility, and infrastructure conditions of technology, emphasizing the driving role of technological capability. Within the framework of green growth, R&D investment is a critical force driving breakthroughs in green technologies, particularly in fields such as low-carbon technologies and clean energy. By increasing R&D investment, technological innovation can be promoted to overcome current technical bottlenecks, thereby facilitating the widespread application of green technologies. The diffusion of technological innovation enables these innovations to rapidly spread to broader domains, especially among less developed areas and small and medium-sized businesses. This ensures that the spread of environmentally friendly technologies is not confined to economically advanced areas, promotes the inclusiveness of social welfare, and consequently drives IGG.

Secondly, the organizational dimension encompasses the internal structure, resource endowments, management capabilities, and strategic orientation of an organization, which determine its efficiency in absorbing and transforming technologies. The structure of human capital and industrial organization within a city fundamentally shapes its foundational conditions for absorbing and applying green technologies. A high-quality human capital pool enhances the innovation and R&D capabilities of enterprises, facilitating the quick development and use of green technologies. Concurrently, the industrial structure's optimization, particularly the green revolution of high-pollution and high-energy-consuming industries, serves as a key pathway for achieving green growth. By optimizing the industrial structure, not only can the application of green technologies be promoted, but employment opportunities can also be provided for broader social groups, thereby advancing socially inclusive green growth.

The environmental dimension includes outside variables such as policies and regulations, competition in the market, and regional economic conditions, which provide support or constraints for technological application. In the context of IGG, both the hard constraints imposed by policies and regulations and the soft constraints exercised through public and media supervision are equally important. Governments establish clear environmental standards and targets, employing mandatory measures for environmental regulation to restrict corporate emissions and ensure that enterprises fulfill their environmental responsibilities. Simultaneously, the public, media, and social groups exert soft constraints through social discourse and public oversight, encouraging enterprises to place greater emphasis on environmental protection and pollution control. This dual pressure and impetus collectively foster the advancement of IGG. Based on the internal mechanisms of IGG within the aforementioned TOE theoretical framework, this paper provides a detailed analysis as follows.

3.2.2.1 Analysis of the mediating role based on the technical dimension

At the technological dimension, by increasing R&D spending and promoting the spread of technical innovation, the "dual pilot" approach advances IGG.

Concerning the connection between R&D investment and the innovation-driven "dual pilot" policy, both the ICP and the NIIDZ policy effectively stimulate corporate R&D investment through measures such as fiscal subsidies, tax incentives, innovation platform development, incentives for the commercialization of scientific and technological advancements as well as the recruitment of top individuals. Concerning the link between R&D investment and IGG, the central idea of endogenous growth theory holds that technical advancement and knowledge accumulation are the primary drivers of long-term economic growth. Increasing R&D investment effectively expands the knowledge stock, accelerates the iteration speed of green technologies, and thereby enhances overall social productivity (Guerrero et al., 2021), thus fostering sustainable economic growth. Moreover, R&D investment can spur the emergence of new industries while strengthening the overall competitiveness and resilience of industrial chains (Sawang and Unsworth, 2011), injecting new momentum into economic growth.

Concerning the connection between the diffusion of technological innovation and the innovation-driven "dual pilot" policy, innovation diffusion theory posits that the rate of diffusion for a new technology depends on its relative advantage, compatibility, complexity, trialability, and observability. On one hand, the ICP lowers the financial barriers and initial risks for enterprises to adopt and apply green technologies through dedicated funding support, highlighting its economic relative advantage. Simultaneously, the policy prioritizes establishing public service platforms, including proof-of-concept and pilot-scale maturation facilities, effectively transforming laboratory technologies into observable and testable mature solutions. This significantly enhances the "observability" and "trialability" of technology diffusion, providing clear learning models and decision-making references for potential adopters. On the other hand, the NIIDZ policy conducts pioneering experiments in areas such as property rights systems, project organization, and innovation services. By implementing list-based and standardized management and establishing integrated service systems, it significantly simplifies the process of technology transfer and commercialization, facilitates the alignment of technological innovation with industry and market needs, and thereby reduces the "complexity" and "compatibility" issues associated with technology diffusion.

Regarding the connection between IGG and the diffusion of technological innovation, the diffusion process of green technologies is, in essence, a transformation of technological dividends into comprehensive economic, environmental, and social benefits. On one hand, the diffusion process helps bridge the green technology gap across different regions and enterprises, encouraging more firms to adopt green technologies and driving the overall green transformation of industrial chains. This, in turn, generates new industrial employment opportunities in areas such as green manufacturing and new energy services, fostering green employment. On the other hand, the environmental improvements and community development projects resulting from technology diffusion contribute to enhanced community wellbeing and equity, strengthening the inclusivity and sustainability of IGG.

Based on this, this paper proposes Hypothesis 3: At the technological dimension, R&D investment and technological innovation diffusion play mediating roles in the process through which the "dual pilot" policy promotes IGG.

3.2.2.2 Analysis of the mediating role based on the organizational dimension

At the organizational dimension, the "dual pilot" policy promotes IGG by enabling the advancement of human capital and facilitating the optimization of industrial structure.

In terms of the relationship between the development of human capital and the innovation-driven "dual pilot" policy, this policy successfully encourages the advancement of the human capital structure toward higher levels. On the one hand, the ICP directly increases the cultivation and supply of high-level innovative talent through special funding to support research universities, scientific research institutes, and industry-academia collaboration platforms. On the other hand, the NIIDZ, by piloting reforms in talent evaluation, incentive, and mobility mechanisms, optimizes the innovation incentive environment, effectively attracting and aggregating high-end talent. Concerning the link between human capital advancement and IGG, based on knowledge spillover theory, knowledge spillovers serve as a significant driver of economic growth and productivity enhancement. The high-level talent concentrated in "dual pilot" cities, possessing cutting-edge knowledge and innovative capabilities, fosters the spillover, recombination, and recreation of green frontier knowledge within innovation networks through frequent R&D collaborations, technical exchanges, and informal interactions. This process catalyzes new green technologies, enhancing both the scale and quality of regional green technological innovation outputs. Consequently, it provides society with cleaner production processes and lower-carbon energy technologies, fundamentally promoting the combined advantages of carbon mitigation and pollution reduction, thereby decoupling economic growth from resource and environmental pressures.

Regarding the relationship between the innovation-driven "dual pilot" policy and industrial structure optimization, according to industrial evolution theory and structural change theory, the policy guides and reallocates resources to propel regional industrial structures toward higher-level development (Lin et al., 2023). Both the ICP and the NIIDZ policy systematically direct capital and technology from traditional high-energy-consuming industries toward high-tech industries and modern service sectors by providing technological transformation subsidies and tax incentives. This promotes the upgrading of traditional industries and the formation of emerging industrial clusters. Concerning the link between industrial structure optimization and IGG, the evolution of industrial structure toward greener and more advanced directions directly determines the quality and inclusivity of growth. The expansion of green, low-carbon industries such as modern services and high-end manufacturing enhances a region's capacity to withstand external shocks, ensures long-term stability in the job market, and creates numerous new positions requiring intermediate to advanced skills. This fosters coordinated development of economic, environmental, and social resilience.

In light of this, this study puts forth Hypothesis 4: At the organizational dimension, the advancement of human capital and the "dual pilot" policy's promotion of IGG is mediated by the optimization of industrial structure.

3.2.2.3 Analysis of the mediating role based on the environmental dimension

At the environmental dimension, the "dual pilot" policy promotes IGG by establishing and strengthening a dual regulatory mechanism comprising formal and informal environmental regulations.

Regarding the relationship between the innovation-driven "dual pilot" policy and formal environmental regulation, the ICP explicitly lists green development as a key objective. It sets binding targets, such as reducing major pollutant emissions, as key performance indicators for monitoring and evaluating local governments' efforts in building innovative cities. Additionally, it adopts proactive fiscal and monetary policies to incentivize corporate investment in environmental technology R&D and green production. The NIIDZ, in its development plans, bans initiatives in sectors with high levels of pollution, energy consumption, and environmental danger, while emphasizing the promotion of green transformation for traditional industries.

Based on public supervision theory, informal environmental regulation is an essential adjunct to formal regulation in the interaction between the innovation-driven "dual pilot" policy and informal environmental regulation. Public environmental expectations are raised by the creation of "dual pilot" demonstration cities and their expected management objectives. Through channels such as municipal supervision platforms for reporting and providing feedback, public opinion pressure and supervisory oversight exert informal constraints on corporate production and operational activities.

Concerning the link between dual environmental regulations and IGG, their synergistic interaction constructs a solid foundation for promoting IGG. According to the Porter Hypothesis, well-designed environmental regulations can stimulate an "innovation compensation" effect. On one hand, the "dual pilot" policy, through mandatory measures, supervises and restricts corporate emission behaviors, clarifying the direction and cost compensation for green transition. On the other hand, social supervision stemming from informal regulation continuously applies external pressure, thereby expanding the market demand for green products. The combination of both compels and incentivizes enterprises to proactively pursue

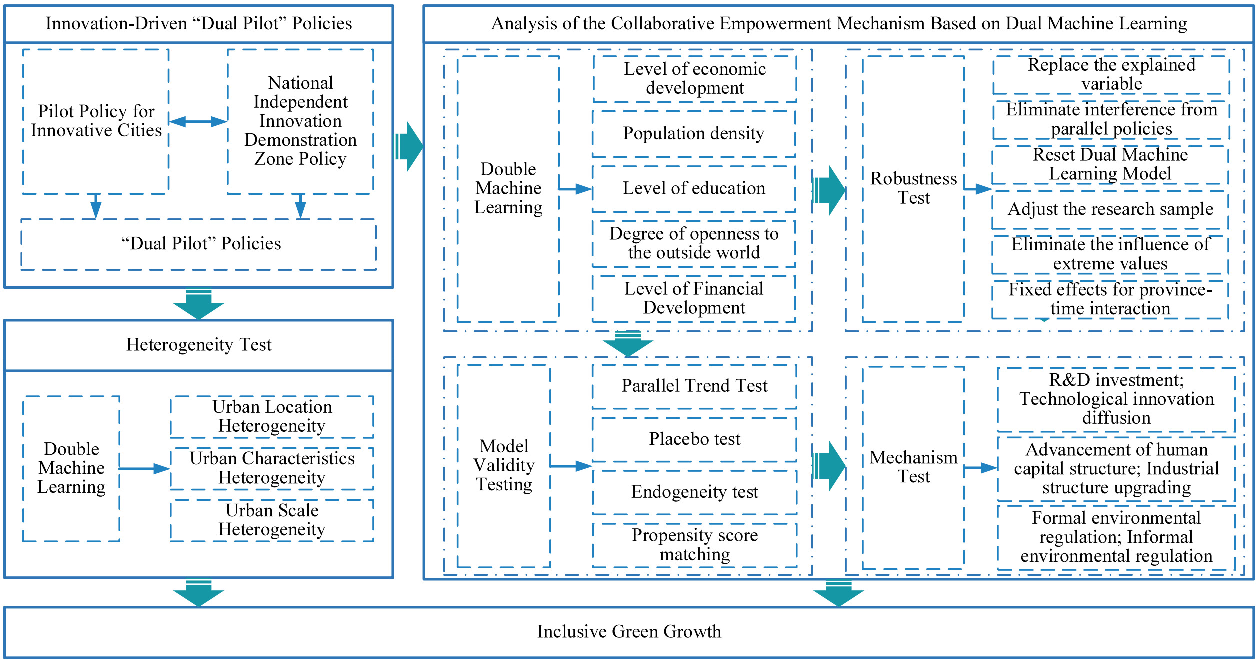

FIGURE 2
Research framework diagram.

green technology innovation to address compliance costs and build competitive advantages. This triggers the innovation compensation effect, generating dual dividends in environmental governance and green technology innovation. It simultaneously enhances urban innovation capacity and environmental quality, thereby driving IGG.

In light of this, this study puts forth Hypothesis 5: Formal and informal environmental laws mediate the process by which the "dual pilot" approach advances IGG at the environmental level.

Figure 2 depicts the research framework for this paper, which is based on the theoretical analysis and research hypotheses mentioned above.

4 Model establishment and variable measurement

4.1 Model establishment

The development of IGG is a complex and dynamic multi-dimensional process, characterized by rich connotations and the synergistic interaction of various elements. Its progress is not the result of a single factor. Therefore, when assessing the synergistic effects of the "dual pilot" policy on urban IGG, to guarantee the reliability and scientific validity of the estimation results, other potential confounding factors must be sufficiently controlled for. However, traditional causal inference methods may suffer from estimation bias due to model misspecification and redundancy in control variables when handling high-dimensional controls, potentially compromising the robustness of the findings. The double machine learning approach provides clear benefits in variable selection and model estimate as compared to conventional causal inference models (Chen and Shen, 2024). It can overcome the dual pitfalls of biased estimation and the dimensionality curse that results from nonlinear relationships among variables, while also addressing challenges such as large biases in machine learning and difficulties in constructing confidence intervals. Furthermore, it enhances the accuracy of causal inference under bidirectional fixed effects with control variables, providing a reliable, asymptotically normal, and effective semi-parametric approach for causal estimating (Xie et al., 2024). Consequently, this paper adopts the double machine learning approach proposed by Chernozhukov et al. (2018) to evaluate the impact effects of the innovation-driven "dual pilot" policy on IGG:

$$IGG_{it} = \theta_0 Innovcity \times Demozone_{it} + g(X_{it}) + \varepsilon_{it} \tag{1}$$

$$E\left(\varepsilon_{it} \middle| X_{it}, Innovcity \times Demozone_{it}\right) = 0 \tag{2}$$

In Equations 1, 2, i denotes the city, and t denotes the year. IGG_{it} represents the dependent variable, namely, inclusive green growth. $Innovcity \times Demozone_{it}$ is the core explanatory variable, indicating cities that simultaneously implement the ICP and NIIDZ policies. If city i implements the "dual pilot" policy from year t onwards, $Innovcity \times Demozone_{it}$ equals 1; otherwise, it is 0. θ_0 is the main treatment coefficient that this paper is interested in. If θ_0 is statistically significant and favorable, suggesting that the "dual pilot" policy encourages IGG in the pilot cities. X_{it} is a collection of control variables with high dimensions; ε_{it} is the random error term, satisfying the condition of zero conditional mean.

TABLE 1 Inclusive green growth indicator system in china.

Primary indicator	Secondary indicator	Quality	Unit	Optimal projection direction	Weight
Economic growth	Regional GDP growth rate	+	%	0.0468	0.0022
	GDP *per capita*	+	RMB per person	0.3562	0.1269
	Secondary industry share	-	%	0.1304	0.0170
	The tertiary sector's share	+	%	0.2121	0.0450
Social equity	Urban dwellers' *per capita* disposable income	+	RMB per person	0.3384	0.1145
	Rural dwellers' *per capita* disposable income	+	RMB per person	0.3216	0.1034
	Share of the workforce employed in the secondary industry	+	%	0.0926	0.0086
	Share of employees in the tertiary sector	+	%	0.0937	0.0088
	Number of hospital beds in hospitals and health centers	+	Beds	0.2286	0.0522
	Number of participants in the basic pension insurance scheme for urban employees	+	No.	0.2318	0.0537
	The number of urban and rural residents enrolled in the basic medical insurance scheme	+	No.	0.1331	0.0177
	The quantity of people enrolled in unemployment insurance	+	No.	0.2260	0.0511
Environmentally friendly	Industrial wastewater discharge volume	-	t	0.0722	0.0052
	Industrial wastewater discharge compliance volume	+	t	0.1681	0.0282
	Industrial sulfur dioxide emissions	-	t	0.1039	0.0108
	Household waste treatment rate	+	%	0.4675	0.2186
	Rate of complete use of industrial solid waste	+	%	0.1658	0.0275
	Sewage treatment plants' centralized treatment rate	+	%	0.3295	0.1086

Simultaneously, to apply the double machine learning algorithm for the main regression and reduce estimating mistakes brought on by bias in regularization as much as possible, the paper constructs the auxiliary regressions:

$$Innovcity \times Demozone_{it} = m(X_{it}) + \mu_{it} \tag{3}$$

$$E(\mu_{it}|X_{it}) = 0 \tag{4}$$

In Equations 3, 4, $m_0(X_{it})$ represents the treatment variable's regression function on the collection of high-dimensional control variables, while η_{it} denotes the random error term. The specific steps for estimating policy effects through a double machine learning model are as follows: First, estimate the particular functional form $\hat{m}(X_{it})$ of the auxiliary regression $m_0(X_{it})$) using machine learning algorithms, and calculate the estimated residual value $\hat{\mu}_{it} = Innovcity \times Demozone_{it} - \hat{m}(X_{it})$; Second, the particular functional form $\hat{g}(X_{it})$ of $g(X_{it})$ in the main regression is once more estimated using the machine learning approach. The primary regression's functional form is then rewritten as $IGG_{it} - \hat{g}(X_{it}) = \theta_0 Innovcity \times Demozone_{it} + \varepsilon_{it}$; Finally, use the estimated $\hat{\mu}_{it}$ as a treatment variable's instrumental variable from the first step $Innovcity \times Demozone_{it}$ in the main regression. This yields an unbiased estimate θ_0 for the treatment variable coefficient.

4.2 Variable selection

4.2.1 Dependent variable

Based on the preceding analysis, IGG is a multidimensional and comprehensive concept, representing an economic growth model that integrates both inclusive growth and green growth. Considering that existing studies often define IGG from the perspective of its constituent elements, it is typically seen as a combination of social justice, ecological sustainability, and economic progress. Therefore, drawing on the research of Fan et al. (2023), this paper constructs a measurement index system for IGG based on three core dimensions: economic growth, social equity, and environmentally friendly. This system aims to comprehensively assess development efficiency, inclusivity, and sustainability. The specific indicators are detailed in Table 1.

This research uses the projection pursuit method based on an accelerated genetic algorithm for assessment because the IGG indicators are multidimensional. This method determines the optimal projection direction by globally optimizing the projection index function $Q(a)$, thereby transforming high-dimensional data into a low-dimensional subspace and obtaining the one-dimensional output projection value $z(v)$ for the IGG indicator.

$$\begin{cases} maxQ(a) = S_S \cdot D_z \\ s.t.\sum_{j=1}^{n} a^2(j) = 1 \end{cases} \quad (5)$$

$$z(v) = \sum_{j=1}^{n} a(j) y(v, j) \quad (6)$$

In Equations 5, 6: $Q(a)$ denotes the projection index function; S_z represents the standard deviation of $z(v)$; D_z signifies the local density of $z(v)$; $a(j)$ indicates the projection direction for indicator j, where the weight of each indicator is the square of the corresponding component of the optimal projection direction vector, and the sum of these weights equals 1; $z(v)$ represents the projection value of the IGG index; v denotes the v th sample; and $y(v, j)$ is the dimensionless normalized value of the j th sub-indicator for the v th sample.

4.2.2 Explanatory variable

This paper's primary explanatory variable is the "dual pilot" policy, which is driven by innovation ($Innovcity \times Demozone_{it}$), represented by the interaction term between the policy dummy variable $Innovcity_{it}$, which denotes the ICP, and the policy dummy variable $Demozone_{it}$, which denotes the NIIDZ policy. This interaction term captures the policy treatment effect of simultaneously implementing both policies. Specifically, if city i is approved as an ICP in year t, then $Innovcity_{it}$ equals 1; otherwise, it is 0. Similarly, if city i is approved as a NIIDZ in year t, $Demozone_{it}$ equals 1; otherwise, it is 0. The interaction term $Innovcity \times Demozone_{it}$ indicates that if city i implements the "dual pilot" policy in year t, then $Innovcity \times Demozone_{it}$ equals 1; otherwise, it is 0.

4.2.3 Mediating variables

Six factors from the three "technology–organization–environment" dimensions are chosen as mechanism variables in this research based on the TOE theory: R&D investment, technological innovation diffusion, advancement of human capital structure, industrial structure upgrading, formal environmental regulation, and informal environmental regulation:

1. R&D investment ($R\&D_{it}$). One of the most important factors influencing technological innovation and R&D activity in businesses is R&D expenditure. By increasing R&D investment, firms can introduce more advanced technologies and equipment, cultivate high-quality R&D personnel, and stimulate innovation vitality, thereby promoting IGG at the technological level. The percentage of scientific spending in the regional GDP is used to gauge R&D investment, in accordance with the methodology of Jiang and Chen (2025).
2. Technological innovation diffusion ($Diffusion_{it}$). The diffusion of innovative technologies primarily reflects their market activity. Therefore, drawing on the method of Kang and Wang (2024), the growth rate of invention patent applications, the volume of transactions in the technology market, and the sales revenue of new goods from industrial businesses larger than a certain size are used to build an indicator system. The level of technological innovation diffusion is then calculated using the entropy method.
3. Advancement of human capital structure ($Human_{it}$). Advanced human capital, possessing richer professional knowledge and higher skill levels, exhibits greater efficiency in technology application. Its agglomeration effect optimizes organizational resource allocation, drives industrial upgrading, and consequently promotes IGG at the organizational level. Drawing on the method of Zhou and Ren (2023), this paper measures the human capital structure advancement index using the vector angle method. The particular method of computation is as follows: Based on educational achievement, human capital is first divided into five groups: primary school, junior high school, senior high school, college and above, and illiterate/semi-literate. The proportions of these five categories form a five-dimensional vector $X_0 = (X_{0,1}, X_{0,2}, X_{0,3}, X_{0,4}, X_{0,5})$. A set of standard orthogonal basis vectors is established as a reference system: $X_1 = (1, 0, 0, 0, 0)$, $X_2 = (0, 1, 0, 0, 0)$, $X_3 = (0, 0, 1, 0, 0)$, $X_4 = (0, 0, 0, 1, 0)$, $X_5 = (0, 0, 0, 0, 1)$. Equation 7 is used to calculate the angle θ_j between the human capital structure vector X_0 and each basis vector X_j ($j = 1, 2, 3, 4, 5$). Finally, by determining the weight for each θ_j and applying Equation 8, the human capital structure advancement index is derived.

$$\theta = \arccos\left(\frac{\sum_{i=1}^{5}(x_{j,i} \cdot x_{0,i})}{\sqrt{\sum_{i=1}^{5} x_{j,i}^2} \cdot \sqrt{\sum_{i=1}^{5} x_{0,i}^2}}\right) \quad (7)$$

$$Human_{it} = \sum_{j=1}^{5}(W_j \cdot \theta_j) \quad (8)$$

In Equation 7, $x_{0,i}$ represents the i th component of the human capital space vector X_0, while $x_{j,i}$ denotes the i th component of the basic vector set X_j ($j = 1, ..., 5$). In Equation 8, W_j denotes the weight of θ_j. Given the monotonically decreasing nature of the inverse cosine function, this study assigns the following weights to each indicator: θ_1 through θ_5 are successively assigned values of 5, 4, 3, 2, and 1.

Given the limitations of prefecture-level city data, this research uses the approach suggested by Luo (2021). It calculates the prefecture-level city human capital structure advancement index by weighting the city's GDP share within the provincial GDP total and multiplying it by the relevant human capital structure advancement index data at the province level.

1. Industrial structure upgrading ($Structure_{it}$). Industrial structure upgrading refers to the process or trend of transitioning from a lower-level industrial structure to a higher-level one. It is essential to achieving IGG and entails a transition from labor-intensive to technology- or knowledge-intensive sectors. According to Shi et al. (2024), the ratio of the tertiary industry's added value to that of the secondary industry is used to gauge the degree of industrial structure upgrading.
2. Formal environmental regulation (FER_{it}). Formal environmental regulation refers to government-mandated environmental supervision, which involves monitoring and setting explicit environmental standards and targets through

TABLE 2 Descriptive statistics.

Variables	N	Mean	S.D.	Min	Max
IGG_{it}	4522	1.5360	0.3051	0.6731	3.0121
Innovcity × $Demozone_{it}$	4522	0.0548	0.2277	0	1
$Pergdp_{it}$	4522	10.5404	0.7265	4.5951	13.0557
$People_{it}$	4522	5.9000	0.6912	2.8685	8.1362
$Education_{it}$	4522	0.1791	0.0419	0.0177	0.3774
$Open_{it}$	4522	0.1890	0.3224	0.0000	3.4987
$Finance_{it}$	4522	16.2709	1.3278	12.6637	20.6876

compulsory measures to restrict corporate emissions, thereby promoting IGG at the environmental level. Drawing on the method of Liu (2023), this study uses the logarithmic form of industrial sulfur dioxide emissions to quantify the degree of formal environmental regulation in urban areas.

3. Informal environmental regulation (IER_{it}). Informal environmental regulation primarily refers to negotiations or even confrontations between the public, media, social organizations, and polluting enterprises, reflecting public attention to issues such as environmental protection and pollution control. As mobile devices continue to proliferate and information infrastructure continues to develop, the internet has become a vital channel for the public to express demands and participate in social governance, leveraging its high exposure, low barriers to entry, and low cost. Drawing on the research of Chen et al. (2025), this paper measures the level of informal environmental regulation in cities by using the natural logarithm of the search volume retrieved from the Baidu search engine using "environmental protection" as the keyword for the corresponding cities.

4.2.4 Control variables

Considering the body of current literature, the following control variables were established: 1. Economic development level ($Pergdp_{it}$), measured by the logarithm of regional *per capita* GDP. 2. Population density ($People_{it}$), measured by the logarithm of urban registered population. 3. Education level ($Education_{it}$), represented as the logarithm of education expenditure within general budgetary spending. 4. Degree of openness ($Open_{it}$), characterized by the ratio of regional import and export volume to GDP. 5. Level of financial development ($Finance_{it}$), represented as the logarithm of outstanding loans from financial institutions at the end of the year.

4.3 Data sources and descriptive statistics

This analysis uses panel data from 266 Chinese cities between 2006 and 2022, excluding cities with significantly missing data based on data availability. The relevant indicator data are primarily sourced from the *China City Statistical Yearbook*, *China Urban Construction Statistical Yearbook*, provincial statistical yearbooks, and other publicly available materials. Linear interpolation is used to fill in missing data for some variables. Table 2 displays the descriptive statistics.

5 Empirical testing and discussion of results

5.1 Model estimation results

This study uses a twofold machine learning model to estimate the synergistic effect of the innovation-driven "dual pilot" policy on IGG and builds on the work of Zhang and Li (2023) to investigate the direct impact of the policy on IGG. In the estimation process, a five-fold cross-validation approach is applied to the sample set, and the Lasso regression algorithm is used to predict the residuals of both the treatment variable and the outcome variable. The regression results are presented in Table 3. Columns (1) to (3) report the estimation results after sequentially incorporating time fixed effects, individual fixed effects, and the linear terms of the control variables. The findings show that the "dual pilot" approach has a significantly favorable promoting effect on IGG at the 1% level, independent of the inclusion of control variables. This supports Hypothesis 1 by indicating that the "dual pilot" approach has a synergistic effect on urban IGG that is noticeably positive. Meanwhile, Column (4) builds upon the model in Column (3) by further incorporating the quadratic terms of the control variables to enhance the precision of the fitted model. The regression result remains significantly positive, providing further evidence for the accuracy of the findings. Hypothesis 1 is thus confirmed.

In order to determine whether a "dual pilot" policy performs better than a "single pilot" approach, following the approach of Meng and Li (2023), this paper modifies Model (1) by replacing the original explanatory variable with dummy variables representing the ICP and the NIIDZ policy as "single pilot" policies, respectively. This makes it possible to examine how a single pilot policy affects IGG. Among them, column (5) reports the impact of the ICP on IGG, with a regression coefficient of 0.0521, which is significantly positive at the 1% confidence level. Column (6) reports the impact of the NIIDZ policy on IGG, with a regression coefficient of 0.0281, which is also significantly positive at the 1% confidence level. The coefficients of both "single pilot" policy dummy variables are clearly significantly positive after adjusting for two-way fixed effects as well as the linear and quadratic terms of the control variables. This suggests that both pilot policies promote IGG. The regression coefficient of the "dual pilot" policy is higher than the total of the coefficients of the single pilot policies, as can be shown by comparing the data in Column (4) with those in Columns (5) and (6). This finding demonstrates that, compared to a single pilot policy, the "dual pilot" policy holds a significant advantage in promoting IGG. Its synergistic effect can more effectively enhance IGG, thereby validating Hypothesis 2.

5.2 Model validity testing

5.2.1 Parallel trend test

Meeting the premise of parallel trends is necessary before evaluating policies, meaning that the treatment group and the

TABLE 3 **Baseline regression results.**

Variables	(1)	(2)	(3)	(4)	(5)	(6)
Innovcity × $Demozone_{it}$	0.4651***	0.1057***	0.1171***	0.0853***		
	(0.0164)	(0.0089)	(0.0091)	(0.0087)		
$Innovcity_{it}$					0.0521***	
					(0.0064)	
$Demozone_{it}$						0.0281***
						(0.0102)
Time-fixed effect	YES	YES	YES	YES	YES	YES
Individual fixed effects	NO	YES	YES	YES	YES	YES
Control variable single term	NO	NO	YES	YES	YES	YES
Control variable quadratic term	NO	NO	NO	YES	YES	YES
Sample size	4522	4522	4522	4522	4522	4522

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent robust standard errors.

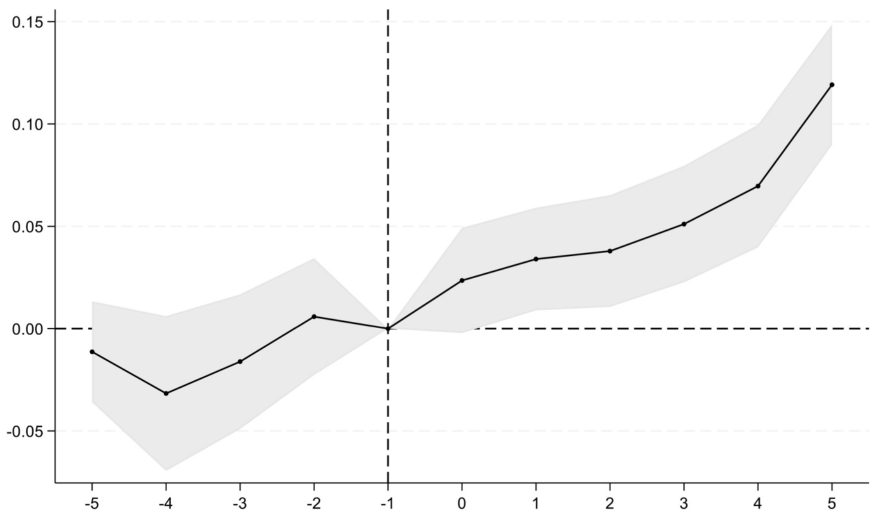

FIGURE 3
Parallel trend test.

control group must exhibit statistically indistinguishable time trend characteristics prior to policy intervention, without significant systematic differences. Therefore, this paper uses the period before the implementation of the innovation-driven "dual pilot" policy as the reference group to conduct the parallel trends test. Simultaneously, to avoid multicollinearity, the year immediately preceding policy implementation is omitted as the base period. Figure 3 displays the parallel trends test findings for the year prior to policy implementation after removing the dummy variable.

Specifically, the pilot city policy's implementation year is denoted by year 0, with −1 to −5 respectively denoting one to 5 years before implementation, and 1 to 5 respectively denoting one to 5 years after implementation. Time fixed effects and individual fixed effects are also included. It is clear that there was no discernible systematic pattern and no notable disparities in the change trends between pilot and non-pilot cities prior to the adoption of the innovation-driven "dual pilot" strategy. Regression coefficients for the innovation-driven "dual pilot" policy on urban IGG, however, vary widely and are all statistically positive during the policy implementation year and the following periods. This suggests that the parallel trends assumption is satisfied by the shifting trends of the impact on IGG between the treatment and control groups.

5.2.2 Placebo test

To exclude interference from unobserved factors, this paper adopts the method used by Han et al. (2024) and conducts a placebo test using a 500-time random repeated sampling approach based on the difference-in-differences model. The regression coefficients,

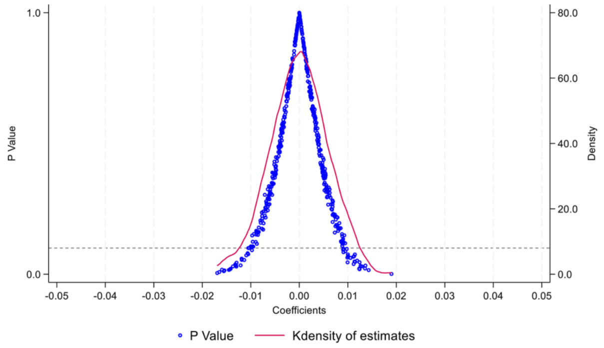

FIGURE 4
Placebo test.

which deviate considerably from the baseline regression coefficients, are clustered around zero and have a normal distribution, as seen in Figure 4. This shows that the innovation-driven "dual pilot" policy's effect on IGG is not influenced by chance, supporting the validity of the study's conclusions.

5.2.3 Endogeneity test

From the standpoint of the subject of the study, a potential causal endogeneity issue may exist between the "dual pilot" policy and IGG. Although this paper has controlled for variables influencing IGG to the greatest extent possible, endogeneity issues arising from omitted variables or bidirectional causality may still persist. In order to reduce the estimation bias brought on by the empirical results' endogeneity, this paper employs the instrumental variable (IV) method and the System GMM method to address endogeneity, respectively.

To resolve potential issues of bidirectional causality and omitted variables in the model, this essay is based on the study of Nunn and Qian (2014) and Li et al. (2025), selecting two sets of cross-sectional data: historical patent counts and urban terrain ruggedness. These are respectively interacted with time trend terms to construct panel instrumental variables IV1 and IV2. The IV method is then applied for estimation. The following justifies the choice of these instrumental variables: From the perspective of relevance, historical patent counts reflect a city's long-term innovation accumulation. Policymakers often prioritize cities with a strong existing innovation base when selecting pilot cities. Terrain ruggedness reflects whether a city's topography is steep; flatter terrain is more conducive to infrastructure development and the formation of large-scale urban clusters and population agglomeration. The "dual pilot" policy tends to be implemented in regions with a solid industrial foundation. Both variables satisfy the relevance assumption for instrumental variables. From the perspective of exogeneity, historical patent counts, as historical values, and terrain ruggedness, as an objectively existing geographical variable, cannot directly influence IGG, satisfying the exogeneity assumption for instrumental variables.

Based on this, the results of the two-stage least squares regression are shown in Table 4's columns (1) and (2). The findings indicate that the effect coefficient of the innovation-driven "dual pilot" policy on IGG is 0.3559, which, at the 1% confidence level, is still substantially positive. This confirms that even after addressing endogeneity issues, the paper's conclusions are still reliable and valid. Furthermore, the Kleibergen-Paap rk LM statistic is 106.5956 with a significant p-value, passing the underidentification test. The Kleibergen-Paap rk Wald F statistic reaches 33.3727, far exceeding the critical value of 19.93 at the 10% significance level, also passing the test for weak instruments, thereby proving the validity of the selected instrumental variables.

Building on this, to strengthen the conclusions' resilience and overcome the potential limitations of the 2SLS method in handling high-dimensional data and complex nonlinear relationships, and to strengthen the interpretability and effectiveness of the endogeneity treatment results, this paper constructs and re-estimates using the double machine learning partially linear instrumental variable model. The outcomes are displayed in Table 4's columns (3) and (4). The findings confirm the robustness of the regression results by showing that the impact coefficients of the innovation-driven "dual pilot" policy on IGG are significantly positive regardless of whether quadratic terms of control variables are included.

Furthermore, this paper also considers incorporating the lagged term of IGG to construct a dynamic panel and employs the System Generalized Method of Moments (GMM) to further account for possible endogeneity in estimate. Column (5) of Table 4 presents the System GMM regression results. The findings demonstrate that the innovation-driven "dual pilot" policy encourages IGG, with the impact coefficient of the policy on IGG remaining considerably positive at the 1% confidence level. The AR (1) test value is 0.0000, and the AR (2) test value is 0.7324, indicating that the model has a first-order serial correlation but no second-order serial correlation. The Hansen test result is 0.2402, indicating no overidentification issue with the instruments, verifying the accuracy of the System GMM estimation results.

It is noteworthy that after addressing endogeneity, both the IV method and the System GMM method consistently demonstrate that IGG benefits greatly from the innovation-driven "dual pilot" policy, thereby further confirming the validity of Hypothesis 1.

5.2.4 Preference score matching

To address potential interference from sample selection bias, in order to evaluate the impact of the innovation-driven "dual pilot" policy on IGG and confirm the robustness of the policy treatment effect, this study uses a combination approach of propensity score matching (PSM) and double machine learning. This study incorporates economic development level, population density, education level, degree of receptivity to the outside world, and financial development level as covariates. A Logit model is used to estimate the propensity scores, and the optimal control group satisfying the common support condition is identified through nearest-neighbor matching one-to-one without replacement. Samples outside the common support range are excluded, resulting in a new dataset. Figure 5 presents the density function plot of the PSM propensity scores. The figure indicates that after matching, the treatment and control groups' propensity score distributions show more similar probability density distributions. This demonstrates satisfactory matching effectiveness across policy scenarios, fulfilling the common trend assumption.

TABLE 4 Endogeneity test.

Variables	Two-stage least squares (2SLS)		Double machine learning model		System GMM
	(1)	(2)	(3)	(4)	(5)
	Innovcity × $Demozone_{it}$	IGG_{it}	IGG_{it}	IGG_{it}	IGG_{it}
$L.IGG_{it}$					0.8563***
					(0.0312)
Innovcity × $Demozone_{it}$		0.3559***	0.4920***	0.8059***	0.0802***
		(0.0456)	(0.0683)	(0.1477)	(0.0127)
IV_1	0.0003***				
	(0.0000)				
IV_2	−0.0022***				
	(0.0006)				
Kleibergen-Paap rk LM statistic		106.5956***			
Kleibergen-Paap wald rk F statistic		33.3727			
10% Maximal IV size		{19.93}			
AR (1)					0.0000
AR (2)					0.7324
Hansen					0.2402
Control variable single term	YES	YES	YES	YES	YES
Control variable quadratic term	NO	NO	NO	YES	NO
Time-fixed effect	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES
Sample size	4522	4522	4522	4522	4256

*, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent robust standard errors. The critical values for the Stock-Yogo test are indicated by curly braces.

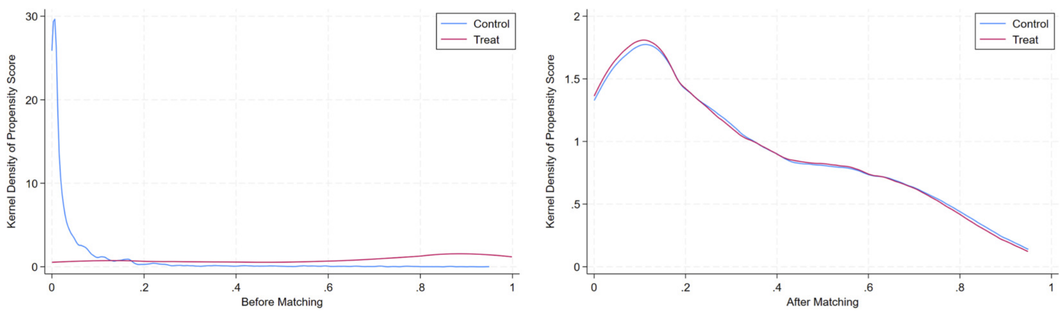

FIGURE 5
Propensity score matching test.

Based on this, after excluding the non-common support portion, this paper re-estimates the impact effect of the "dual pilot" policy on IGG using the double machine learning method. The test results, which are displayed in Table 5, show that the impact coefficients of the innovation-driven "dual pilot" policy on IGG remain significantly positive after mitigating sample selection bias, regardless of whether the quadratic terms of the control variables are included. This confirms the robustness of the regression results.

TABLE 5 Test of tendency score matching.

Variables	(1)	(2)
Innovcity × $Demozone_{it}$	0.1313***	0.1174***
	(0.0143)	(0.0126)
Time fixed effects	YES	YES
Individual fixed effects	YES	YES
Control variable single term	YES	YES
Control variable quadratic term	NO	YES
Sample size	4101	4101

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent robust standard errors.

TABLE 6 Indexing system for urban inclusive green growth in china based on the entropy method.

Primary indicator	Secondary indicators	Quality	Unit	Weight
Economic growth	Regional GDP growth rate	+	%	0.0033
	Per capita GDP	+	RMB per person	0.0635
	Share of secondary industry	-	%	0.0106
	Share of the tertiary sector	+	%	0.0151
Social equity	Per capita disposable income of urban residents	+	RMB per person	0.0468
	Rural dwellers' *per capita* disposable income	+	RMB per person	0.0435
	Share of the workforce employed in the secondary industry	+	%	0.0170
	Proportion of workers in the tertiary sector	+	%	0.0117
	Number of hospital beds in hospitals and health centers	+	Beds	0.0849
	Number of participants in the basic pension insurance scheme for urban employees	+	No.	0.1703
	The number of urban and rural residents enrolled in the basic medical insurance scheme	+	No.	0.1574
	The quantity of people enrolled in unemployment insurance	+	No.	0.2048
Environmentally friendly	Volume of discharged industrial wastewater	-	t	0.0013
	Industrial wastewater discharge compliance volume	+	t	0.1386
	Industrial sulfur dioxide emissions	-	t	0.0010
	Household waste treatment rate	+	%	0.0100
	Rate of complete use of industrial solid waste	+	%	0.0132
	Sewage treatment plants' centralized treatment rate	+	%	0.0070

5.3 Robustness test

5.3.1 Replace the explained variable

To test the robustness of the core conclusions, in this article, the entropy approach is used to quantify the dependent variable instead of the projection pursuit model, which is based on an accelerated genetic algorithm. Accordingly, the urban IGG levels are recalculated. The detailed calculation process of the entropy method is provided in the Supplementary Appendix. The corresponding indicator system and weights for the newly calculated results are presented in Table 6.

Based on this, following the dependent variable's replacement with the new one measured using the entropy method, this paper re-estimates the synergistic effect of the "dual pilot" policy by applying the double machine learning model. Table 7 displays the regression findings. It is evident that, after changing the measurement method of the dependent variable, regardless of whether the quadratic terms of the control variables are included, the impact coefficients of the innovation-driven "dual pilot"

TABLE 7 Replace the explained variable.

Variables	(1)	(2)
Innovcity × $Demozone_{it}$	0.0527***	0.0299***
	(0.0035)	(0.0029)
Time-fixed effect	YES	YES
Individual fixed effects	YES	YES
Control variable single term	YES	YES
Control variable quadratic term	NO	YES
Sample size	4522	4522

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent robust standard errors.

TABLE 8 Removing parallel policy interference.

Variables	(1)	(2)	(3)
	Broadband China	Smart city	Exogenous policy superposition
Innovcity × $Demozone_{it}$	0.0870***	0.0858***	0.0879***
	(0.0087)	(0.0086)	(0.0086)
Control variable single term	YES	YES	YES
Control variable quadratic term	YES	YES	YES
Time-fixed effect	YES	YES	YES
City fixed effects	YES	YES	YES
Sample size	4522	4522	4522

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent robust standard errors.

policy on IGG remain significantly positive, consistent with the main regression results.

5.3.2 Eliminate interference from parallel policies

To exclude potential interference from related policies within the research period, this paper draws on the research of Zhang and Ma (2025) and identifies two potentially confounding policies: Broadband China and Smart City. Among these, the core of the "Broadband China" policy lies in constructing high-speed, ubiquitous, and secure information infrastructure to enhance the physical coverage and access capabilities of information and communication networks and close the gap in digital access. The core of the "Smart City" policy involves utilizing digital technologies such as big data and artificial intelligence to optimize urban governance and services, improve the intelligence and refinement of urban management, and empower economic development and public service delivery. Since the implementation timelines of these two policies overlap with the innovation-driven "dual pilot" policy examined in this paper, and their shared emphasis on goals such as using digitalization to enhance efficiency and promote inclusive services may potentially influence the efficiency, equity, and sustainability objectives pursued by IGG, they could interfere with identifying the overall result of the "dual pilot" policy. Therefore, this paper generates dummy variables for the aforementioned policies using the same method as for generating the core explanatory variable and includes them in the control variables of the baseline regression to mitigate the interference from these policies.

Table 8 displays the regression findings. Columns (1) and (2) show the regression results controlling for the influence of only one of these policies, respectively. Column (3) presents the result controlling for both the Broadband China and Smart City policies simultaneously, i.e., the estimation result including both policy dummy variables in the control variables. The findings show that the impact coefficient of the innovation-driven "dual pilot" policy on IGG is still significantly favorable at the 1% confidence level when other contemporaneous relevant policies are taken into account. Additionally, the coefficient's sign and significance level continue to be quite consistent with the findings of the baseline regression. This suggests that, even after controlling for the interference from these two concurrent policies, the innovation-driven "dual pilot" policy continues to significantly promote IGG, which is in line with the primary regression findings.

5.3.3 Reset double machine learning model

By re-specifying and re-estimating the double machine learning model, this paper builds on the work of Zhang and Li (2023) to prevent possible specification bias in the model. On one hand, the

TABLE 9 Reset double machine learning model.

Variables	(1)		(2)			
	Adjust the sample partitioning ratio		Replace the machine learning model			
	Kfolds = 3	Kfolds = 7	Random forest	Gradient boosting	Neural network	Support vector machine
Innovcity × $Demozone_{it}$	0.0798***	0.0829***	0.0607***	0.0436***	0.1275***	0.0723***
	(0.0086)	(0.0085)	(0.0117)	(0.0117)	(0.0115)	(0.0108)
Control variable single term	YES	YES	YES	YES	YES	YES
Control variable quadratic term	YES	YES	YES	YES	YES	YES
Time fixed effects	YES	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES	YES
Sample size	4522	4522	4522	4522	4522	4522

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent robust standard errors.

TABLE 10 Other robustness tests.

Variables	(1)		(2)		(3)
	Adjust the research sample		Tail trimming		Fixed effects for province-time interaction
	Exclude certain cities	Adjust the research interval	1% tail trimming	5% tail trimming	
Innovcity × $Demozone_{it}$	0.0590***	0.0500***	0.0760***	0.0183**	0.0832***
	(0.0077)	(0.0073)	(0.0081)	(0.0073)	(0.0085)
Control variable single term	YES	YES	YES	YES	YES
Control variable quadratic term	YES	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES
Province-time fixed effects	NO	NO	NO	NO	YES
Sample size	4454	3458	4522	4522	4522

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent robust standard errors.

model is reconfigured by altering the sample splitting ratio (adjusted from 1:4 to 1:2 and 1:6), followed by re-estimation. On the other hand, the Lasso regression algorithm originally used in the model is replaced with random forest, gradient boosting, neural network, and support vector machine methods, respectively, to reconfigure the double machine learning model. Table 9 displays the regression results following the double machine learning model's reconfiguration. Clearly, neither adjusting the sample splitting ratio nor modifying the machine learning algorithm alters the conclusion that urban IGG is promoted by the "dual pilot" policy. These results are still in line with the primary regression findings.

5.3.4 Adjust the research sample

To avoid interference from the administrative advantages among municipalities directly administered by the federal government in the examination of city patterns at the prefecture level, this essay does not include the sample data of such municipalities and retains samples from other cities for regression analysis. Meanwhile, considering the substantial data gaps for cities before 2009 (despite interpolation to address missing values), to avoid bias, the study period is also adjusted to 2010–2022 for re-estimation. Column (1) of Table 10 presents the regression results after adjusting the sample. It is evident that the

TABLE 11 **Heterogeneity test.**

Variables	(1) Eastern cities	(2) Central and western cities	(3) Resource-based cities	(4) Non-resource cities	(5) Major-sized cities	(6) Small and medium-sized cities
Innovcity × $Demozone_{it}$	0.1117***	0.0493***	0.0284	0.0931***	0.0896***	0.0755***
	(0.0115)	(0.0122)	(0.0241)	(0.0091)	(0.0099)	(0.0171)
Control variable single term	YES	YES	YES	YES	YES	YES
Control variable quadratic term	YES	YES	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES	YES
Sample size	1700	2822	1802	2720	748	3774
P value	0.0000		0.0000		0.0000	

*, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. Values in parentheses represent robust standard errors. The P-values for testing differences between coefficient groups in the heterogeneity analysis were calculated using Fisher's combined test (based on 1,000 simulations).

promoting effect of the "dual pilot" policy on IGG remains significant, indicating the robustness of the main regression results.

5.3.5 Eliminate the influence of extreme values

All continuous variables, with the exception of the treatment variable, are winsorized at the 1% level on both tails to prevent estimate bias brought on by outliers. The results are shown in Table 10s column (2) after the impact of extreme values is eliminated. The robustness of the main regression results is confirmed by the results, which demonstrate that the estimated coefficient stays significantly positive, indicating that the conclusion holds even after removing the interference of outliers.

5.3.6 Province-time interaction fixed effects

Given the central role of provinces in China's governance system, cities within the same provincial jurisdiction often exhibit a degree of convergence. To eliminate potential interference from inter-provincial differences and temporal variations on the research findings, the baseline regression in this study also includes province-time interaction fixed effects. Column (3) of Table 10 presents the re-estimated results, which remain significantly positive. This lends more credence to the finding that, in line with the primary regression results, the "dual pilot" policy considerably improves IGG.

5.4 Heterogeneity test

Considering that regression based on the full sample may obscure potential heterogeneity in the impact of the "dual pilot" policy on IGG due to varying city attributes, this paper draws on the research of Ding et al. (2025) to examine the diverse impacts of the innovation-driven "dual pilot" policy on IGG according to three-dimensional city attributes: "location, characteristics, and size."

5.4.1 Testing for urban location heterogeneity

To investigate the heterogeneous impact stemming from urban geographic location, based on their physical locations, the sample cities are divided into eastern, central, and western areas. Regression tests of the baseline model are then conducted separately on these subgroups. Table 11's columns (1) and (2) display the findings. Furthermore, Fisher's combination test method is employed to statistically examine the disparity between the two groups' regression coefficients, ensuring result comparability. Subsequent heterogeneity analyses are handled similarly.

The findings demonstrate that the between-group difference test is passed by the subgroup regression results. The "dual pilot" program has a more noticeable positive effect on IGG in the eastern region than in the central and western regions. This discrepancy primarily stems from systematic differences in institutional environments between the two types of regions. According to institutional isomorphism theory, influenced strongly by the external environment, organizations or regions actively imitate the institutions and practices of those considered successful models within the same environment to gain legitimacy, resources, and ensure survival. The eastern region, serving as the forefront of China's national reform, opening-up, and institutional innovation, has already taken the lead in establishing a series of mature and internationally aligned institutional systems in areas such as judicial protection of intellectual property rights, green finance standards, and the distribution of benefits from scientific and technological achievement commercialization. This aligns with the findings of Wang et al. (2025b). This effect is fully exemplified in Shenzhen: as the first innovative policy pilot city in eastern China and the nation, it took the lead in promulgating the *Shenzhen Special Economic Zone Data Regulations*, establishing a stringent intellectual property protection system, and implementing market-based ecological governance mechanisms such as "carbon credits." This created a strong demonstration and isomorphic effect for other cities in the eastern region, prompting local governments, market entities, and research institutions to rapidly adjust their behaviors to meet these expectations. Consequently, the "dual pilot" policy could be implemented and internalized more efficiently in the eastern region, thereby significantly amplifying the policy effects. In contrast, the institutional evolution in the central and western regions more often manifests as mimetic isomorphism of the mature experiences from the east. Due to their relative lag in pioneering and system integration capabilities for institutional innovation, policy implementation often requires a process of learning, assimilation, and local adaptation. This constrains the speed of institutional response and the depth of execution. Additionally, some cities in the central and western regions may face stronger resource constraints, making the cost of institutional imitation higher or leading to policy distortion and effect dissipation during the adaptation process, thereby affecting the effectiveness of the "dual pilot" policy. Therefore, the innovation-driven "dual pilot" policy has a greater potential to enhance the level of IGG when implemented in cities located in the eastern region.

5.4.2 Testing for heterogeneity in urban characteristics

Considering that the varying resource endowments of cities profoundly influence their development trajectories and innovation responsiveness, according to the city types specified in the State Council's 2013 *National Sustainable Development Plan for Resource-Based Cities (2013–2020)*, this study divides the sample into resource-based and non-resource-based cities. Table 11 displays the regression findings for cities with varying resource endowments in columns (3) and (4). Furthermore, the subgroup regression results passed the between-group difference test, ensuring result comparability.

The findings indicate that while the "dual pilot" strategy has a negligible effect in resource-based cities, it has a significantly beneficial impact in non-resource-based cities at the 1% confidence level. This significant disparity is rooted in the fundamentally different resource endowments of the two types of cities. The resource curse theory states that abundant natural resource endowments can lead to regional over-reliance on a single resource-dependent industrial structure, inhibiting trial-and-error dynamics and innovation vitality. This makes the economic system exceptionally vulnerable to external shocks or technological changes. Conversely, regions lacking such single-resource dependence are often compelled to cultivate a diversified institutional foundation and market ecosystem that supports innovation earlier, thereby possessing structural advantages when responding to innovation policies. Specifically, on one hand, the industrial organizational structure of non-resource-based cities is primarily dominated by manufacturing, modern services, high-tech industries, and strategic emerging industries, emphasizing technological intensity and value-added enhancement. This makes their industrial base more receptive to innovation policy guidance and more capable of transitioning toward green technologies and a knowledge-based economy. The technological linkages and knowledge complementarities existing among different industries within these cities enable core production factors such as knowledge, talent, and data to flow and recombine efficiently across related sectors, thereby fostering synergistic innovation effects more easily. On the other hand, unlike the potentially dominant interest structures associated with a singular industrial structure in resource-based cities, the power and interest structures in non-resource-based cities are typically more pluralistic and decentralized. Their local governments tend to assume the role of "facilitators," actively building collaborative networks with enterprises, universities, and research institutes to reduce internal resistance to policy coordination and implementation. As exemplified by the *Suzhou Intelligent Vehicle Networking Industry Innovation Cluster Action Plan (2023–2025)* released by the Suzhou Municipal Government, which aims to build an integrated industrial chain ecosystem covering "smart vehicles, foundational support, and information interaction" to promote cross-sector collaboration between traditional manufacturing enterprises and software/information service enterprises, translating macro-level innovation-driven policies into localized pathways for industrial digitalization and green upgrading. This governance model, based on pluralistic consultation and service, makes innovation policies more likely to gain broad acceptance and be effectively implemented in non-resource-based cities, thereby achieving green economic growth. In contrast, the prosperity of the resource sector in resource-based cities tends to attract excessive capital concentration in primary extraction and processing activities, thereby weakening local governments' institutional incentives to cultivate long-term competitiveness. This leads to an over-concentration of factor allocation in the resource sector, structurally constraining the space for manufacturing upgrading and R&D activities, inducing a "Dutch disease" effect, consequently affecting the effective functioning of the "dual pilot" policy.

5.4.3 Testing for heterogeneity in city size

Using data from the *Urban Construction Statistical Yearbook* published by the Ministry of Housing and Urban-Rural Development of the People's Republic of China, this paper divides the sample based on a threshold of 3 million permanent residents, taking into account that the innovation spillover effects of the "dual pilot" policy may vary with city population size (Peng and Cao, 2024). Table 11's columns (5) and (6) display the results of the heterogeneity test. Furthermore, the subgroup regression results passed the between-group difference test, ensuring result comparability.

The results indicate that, compared to small and medium-sized cities, in large cities, the innovation-driven "dual pilot" policy works better at raising the IGG level. The underlying reason for this difference lies in the distinct industrial structures of the two city types. According to industrial structure evolution theory, urban scale expansion tends to crowd out traditional industries through rising costs while attracting high-tech industries through market advantages, thereby promoting the formation of a more advanced industrial structure in major-sized cities, dominated by service sectors and advanced manufacturing. This structural advantage enables major-sized cities to more effectively absorb, accommodate, and translate the innovation momentum of the "dual pilot" policy. Specifically, on one hand, the advanced industrial structure of major-sized cities is essentially a dense carrier of knowledge, technology, and high-skilled talent, typically accumulating a deeper and more diverse reserve of technological factors. This advantage is particularly evident in Beijing: as a megacity in China, it has accumulated over 67,000 valid invention patents in the green and low-carbon field alone, constituting a massive localized knowledge repository. Therefore, when the "dual pilot" policy is implemented in such cities, its inherent talent attraction and knowledge diffusion effects are further amplified. The innovation demand guided by the policy can quickly align with the abundant local supply of high-skilled labor, promoting intensive R&D collaboration and knowledge exchange centered on green technologies among enterprises, universities, and research institutions. This efficiently translates policy drive into technological progress, ultimately achieving green and low-carbon transition and resource efficiency improvement. On the other hand, this industrial structure, characterized by modern service sectors and advanced manufacturing clusters, forms a tight network of industrial linkages and synergies. This not only reduces transaction costs and risks across the whole chain from R&D to market for green technologies but also amplifies policy dividends throughout the entire economic system through cross-industry knowledge spillover effects, thereby achieving more inclusive growth. In contrast, the industrial structure of small and medium-sized cities often remains dominated by traditional industries, with a weak foundation in knowledge-intensive sectors, a limited scale of local knowledge repositories, and underdeveloped synergistic networks among industries. This echoes the findings of Wang and Yin (2024): that cities, leveraging their industrial structure advantages, possess more advanced technical infrastructure and advantages in factor aggregation, which can generate more pronounced policy effects. Therefore, when facing the same "dual pilot" policy, the industrial systems of these smaller cities struggle to provide comparable scale and efficiency in knowledge absorption, factor matching, and collaborative innovation support. Consequently, the conversion efficiency and manifestation level of policy dividends are significantly weaker than in major-sized cities.

5.5 Mechanism test

This study examines the indirect effects of the innovation-driven "dual pilot" strategy on urban IGG from the three-dimensional viewpoint of "technology-organization-environment," drawing on the TOE theory. Given the ongoing academic debate regarding potential endogeneity issues in mediation effect models, the study draws on the research of Jiang (2022) and employs a two-step mediation analysis approach by constructing a double machine learning partially linear instrumental variable model for mechanism testing. The analysis's primary regression and auxiliary regression are altered as follows:

$$M_{it} = \theta_2 Innovcity \times Demozone_{it} + g(X_{it}) + \varepsilon_{it} \tag{9}$$

$$Innovcity \times Demozone_{it} = m(X_{it}) + \mu_{it} \tag{10}$$

In Equations 9, 10, M_{it} represents the mechanism variable, while the meanings of the other variables remain as previously defined. Specifically, based on the theoretical framework established earlier, the mechanism variable M_{it} in this paper is examined across the following three dimensions: at the technological level, R&D investment and technological innovation diffusion are selected; at the organizational level, the advancement of human capital and industrial structure upgrading are included; and at the environmental level, both formal and informal environmental regulations are introduced. Table 12 displays the outcomes of the mediation mechanism experiments.

Table 12, columns (1) and (2), demonstrate that from a technological perspective, the innovation-driven "dual pilot" policy significantly promotes IGG by increasing R&D investment and facilitating technological innovation diffusion. This indicates that through fiscal subsidies, tax incentives, and stable innovation expectations, the policy effectively encourages local governments and enterprises to increase funding for scientific research activities. The rise in R&D investment enables and deepens applied research in green technologies and energy-saving processes, accelerating the transformation from laboratory achievements to industrial applications. This provides solutions for reducing production energy consumption and environmental pollution, thereby indirectly enhancing urban IGG. Furthermore, by establishing platforms and demonstrations, the "dual pilot" policy lowers the barriers to identifying and applying green technologies, accelerating their dissemination within industrial chains and further promoting technological innovation diffusion. The rapid diffusion of innovative technologies allows green technologies to quickly permeate all stages of the industrial chain and accelerates their application in broader fields. The widespread adoption of these technologies drives the overall green transformation and energy efficiency improvement of industries while simultaneously generating more green employment. This enables the benefits of environmental improvement and economic growth to be shared more widely, thereby enhancing urban IGG from both efficiency and equity perspectives. Thus, Hypothesis 3 is validated.

Table 12, columns (3) and (4), show that from an organizational perspective, the innovation-driven "dual pilot" policy significantly promotes IGG by optimizing the human capital structure and facilitating industrial structure upgrading. This suggests that the policy can improve the environment for talent development, attract and retain high-end talent, and elevate the level of human capital advancement in cities. Advanced human capital enhances urban entrepreneurial activity and, through knowledge spillovers, R&D collaboration, and high-level entrepreneurship, drives green technology innovation and industrial value chain upgrading, providing rich intellectual capital and innovation momentum for IGG. Simultaneously, the policy channels capital and talent towards high-tech industries, not only fostering the cultivation and development of strategic emerging industries but also accelerating the "transformational pressure" for greening and upgrading traditional industries. Industrial structure upgrading creates more high-skilled jobs, raises overall social income, and makes economic growth less dependent on resource consumption, thereby ensuring high-quality economic growth. Hypothesis 4 is thus confirmed.

Table 12, columns (5) and (6), indicate that from an environmental perspective, the innovation-driven "dual pilot" policy significantly drives IGG by strengthening both formal and informal environmental regulations. This policy mix, oriented towards pollution reduction, reinforces the constraining and guiding role of formal environmental regulations through incentives such as subsidies for green innovation and setting

TABLE 12 Intermediary mechanism test.

Variables	(1) $R\&D_{it}$	(2) $Diffusion_{it}$	(3) $Human_{it}$	(4) $Structure_{it}$	(5) FER_{it}	(6) IER_{it}
Innovcity × $Demozone_{it}$	0.0052***	0.0264***	0.1533***	0.0959***	−0.2658***	0.1792***
	(0.0011)	(0.0032)	(0.0590)	(0.0202)	(0.0297)	(0.0138)
Control variable single term	YES	YES	YES	YES	YES	YES
Control variable quadratic term	YES	YES	YES	YES	YES	YES
Time-fixed effect	YES	YES	YES	YES	YES	YES
City fixed effects	YES	YES	YES	YES	YES	YES
Sample size	4522	4522	4522	4522	4522	4522

*, **, *** indicate significance at the 10%, 5%, and 1% levels, respectively. The values in parentheses represent robust standard errors.

green technology standards, combined with policies, regulations, and green incentives. This encourages enterprises to proactively undertake environmental technology upgrades and standardize emission behaviors, thereby reducing urban pollutant emissions. Moreover, through the "innovation compensation" effect, it unifies environmental improvement with production efficiency gains, ensuring that green growth is both sustainable and inclusive. Concurrently, the information disclosure and public participation mechanisms advocated by the innovation-driven "dual pilot" policy provide effective channels for informal environmental regulation, represented by supervision from the public, media, and environmental organizations. Public oversight through public opinion oversight and green consumption choices imposes market-based soft constraints on enterprises, prompting them to adopt greener practices to protect their reputation. This transforms social demands into drivers of transformation, thereby enhancing the social responsiveness and inclusivity of the growth process. Hypothesis 5 is thus validated.

6 Discussion

In summary, the findings of this study on the impact of the innovation-driven "dual pilot" policy on IGG are not only robust within the sample region, but the conclusions and mechanisms also possess broad applicability in other countries and regions. Future studies could delve deeper into the unique approaches and experiences of many nations and areas in using innovation policy mixtures to support IGG, offering more insightful information and references for low-carbon and green development worldwide. The following conclusions are drawn from this paper's empirical testing of the mechanisms by which the innovation-driven "dual pilot" program affects IGG.

6.1 The universal impact of innovation-driven "dual pilot" policies on inclusive green growth

This study finds that, within the Chinese context, the innovation-driven "dual pilot" policy, composed of the ICP and the NIIDZ policy, can significantly promote urban IGG, with an impact coefficient of 0.0853. Comparing this coefficient with the mean value of IGG reveals that, under the consequences of the innovation-driven "dual pilot" policy, compared to non-pilot cities, the IGG level of pilot cities rises by 5.55%. In contrast, the impact of a single innovation policy is relatively weaker. This conclusion has also been discussed in existing literature: Xu et al. (2025) found that under the influence of China's pilot program for innovation and green finance reform, the IGG level of pilot cities increased by 5.05% relative to non-pilot cities. Liu et al. (2024) found that under the influence of the ICP, the IGG level of pilot cities increased by 1.78% relative to non-pilot cities. This comparison demonstrates that the policy synergy model represented by the "dual pilot" approach proposed in this paper exhibits stronger driving power for IGG in terms of operational logic and effectiveness compared to traditional single innovation policies. This conclusion is strong not just in China, but the core logic of policy synergy it embodies, as an effective mode of public policy provision, also holds universal value globally. As Rogge and Reichardt (2016) point out in their extended policy mix analysis framework, the success of Germany's energy transition benefited from a synergistic policy system design that went beyond single instruments. This system, with the *Renewable Energy Sources Act* (EEG) as the core demand-pull instrument, complemented and interacted with instruments like the EU Emissions Trading System (ETS). Through consistency, coherence, and credibility, it systematically shaped market expectations and guided technological innovation, thereby accelerating the green transition. Therefore, the promoting effect of other types of policy mixes on inclusive green development can also be anticipated in other regions.

6.2 Heterogeneous effects of innovation-driven "dual pilot" policies on inclusive green growth

The examination of heterogeneity shows that the policy effects exhibit significant variation across the dimensions of "location-characteristics-size" due to differences in institutional environment, resource endowment, and industrial structure. From the perspective of institutional environment differences, policy effectiveness is notably influenced by regional institutional foundations. In terms of geographic location, the eastern region, equipped with more mature market mechanisms and institutional systems, can more effectively absorb and translate policy incentives compared to the central and western regions. A typical example is Shenzhen, as the nation's first innovative pilot city. Its pioneering exploration in establishing a judicial protection system for intellectual property rights and market-based ecological mechanisms like "carbon credits" not only enhanced the implementation efficiency of local policies but also provided a "institutional template" for other eastern cities to reference and emulate, thereby accelerating policy diffusion, learning, and internalization at the regional level.

From the dimension of resource endowment differences, in cities that are not resource-based, the effects of policy are more noticeable, reflecting the significant impact of resource structure on policy responsiveness. Specifically, Suzhou, a typical non-resource-based city, systematically promoted the coordinated upgrading of manufacturing and service industries by issuing the *Suzhou Intelligent Vehicle Networking Industry Innovation Cluster Action Plan*, successfully transforming policy opportunities into drivers for green growth. In contrast, many resource-based cities, constrained by a singular industrial structure and transition Inertia, face higher transition resistance and are prone to plunged into the "resource curse" dilemma, where policy dividends are diluted by the existing structure.

From the dimension of industrial structure differences, the innovation-driven "dual pilot" policy shows more significant effects in major-sized cities. This indicates that the policy, as an innovative combination tool integrating external knowledge infusion and institutional incentives, is highly dependent on the city's stock of technological knowledge and the level of its information technology infrastructure. The practice of Beijing provides real-world evidence: on one hand, its accumulation of over 67,000 valid invention patents in the green and low-carbon field constitutes a vast and comprehensive local knowledge repository, capable of rapidly undertake and deepening policy-driven R&D collaborations and industrial upgrading; on the other hand, the continuous development of digital infrastructures such as the "Big Data Management Platform" and the "Industrial Internet Identifier Resolution System" in Beijing provides enterprises with precise policy matching and transformation services, lowering coordination costs and information obstacles during the innovation and spread of green technology. In comparison, small and medium-sized cities, limited by their traditional industry-dominated industrial structures, have relatively weaker knowledge reserves and digital support capabilities, resulting in relatively lower policy conversion efficiency.

6.3 The indirect impact of innovation-driven "dual pilot" policies on inclusive green growth

This paper verifies that the innovation-driven "dual pilot" policy promotes IGG through multiple mediating mechanisms across the three dimensions of technology, organization, and environment, thereby confirming the validity of relevant classical theories in the context of composite policies. At the technological dimension, the mediating role of R&D investment strongly supports the core argument of endogenous growth theory (Romer, 1990), which holds that R&D and knowledge accumulation are the main drivers of long-term economic upgrading and growth. Simultaneously, the significance of the technological innovation diffusion pathway also corroborates the mechanism proposed by innovation diffusion theory (Moseley, 2004) regarding reducing complexity and enhancing observability to accelerate technology dissemination. This suggests that favorable conditions for the spread of green technology can be effectively shaped by the innovation-driven "dual pilot" policy.

At the organizational dimension, the mediating effect of human capital advancement provides empirical support for the view in knowledge spillover theory (Glaeser et al., 1992) that the agglomeration of high-end talent can drive regional innovation and upgrading through informal interactions and spillovers. Concurrently, the mediating role played by industrial structure optimization aligns with the expectations of industrial evolution and structural change theory, confirming that policy-guided industrial progression toward greener and more advanced directions is a key pathway for enhancing economic resilience, creating high-quality employment, and thereby achieving inclusive growth (Lin et al., 2023).

At the environmental dimension, the mediating role of formal environmental regulation validates the Porter Hypothesis (Porter and Linde, 1995), which suggests that appropriate environmental regulations can stimulate innovation compensation, thereby synergistically improving environmental and economic performance. Furthermore, the mediating pathway of informal environmental regulation, represented by public supervision, is also confirmed. This finding incorporates the informal constraints emphasized by New Institutional Economics into the analytical framework, indicating that beyond strengthening government oversight, the "dual pilot" policy can also mobilize social participation to construct a green governance model involving government, market, and society.

7 Research findings and policy recommendations

7.1 Research findings

IGG serves as a strategic cornerstone for driving economic transformation and upgrading, enhancing development sustainability, and improving global competitiveness. Based on the causal logic of "policy synergy—multidimensional transmission mechanisms—IGG," this paper investigates the effects of the innovation-driven "dual pilot" policy on IGG development. The following are the primary conclusions: First, the innovation-driven "dual pilot" policy, represented by the ICP and the NIIDZ, can effectively promote IGG. Second, the mechanism analysis indicates that the policy can accelerate IGG by increasing R&D investment and accelerating technological innovation diffusion at the technological level, enhancing official and informal environmental rules at the environmental level and encouraging the development of industrial upgrading and human capital structure at the organizational level. Finally, the innovation-driven "dual pilot" policy's effects on IGG vary depending on the situation. The impact of the policy is particularly noticeable in major cities, non-resource-based cities, and cities in eastern areas. Analysis suggests this is closely related to the varying conditions of cities regarding institutional environment, resource endowment, and industrial structure. Therefore, future policy promotion and implementation should systematically account for differences in institutional environments, resource endowments, and industrial structures across cities to promote differentiated, targeted policy design and supportive measures.

7.2 Policy recommendations

The study makes the following policy recommendations in light of the aforementioned conclusions:

First, summarize the construction experience of innovation policy mixes, expand the scope of demonstration cities, and explore more innovation policy combination tools. Previous research finds that cities implementing the "dual pilot" policy can effectively encourage the growth of IGG. Therefore, it is necessary to broaden the extent of application of the innovation-driven "dual pilot" policy and increase support in terms of relevant policy backing, funding investment, and talent resources. The advanced experience and successful practices of demonstration cities in developing IGG should be summarized and promoted to establish a set of operational and replicable institutional design systems. Simultaneously, collaborative cooperation among pilot cities should be strengthened to fully leverage their respective advantages and expertise, fostering a favorable situation of complementary strengths and coordinated development. This will collectively advance the deepening implementation and widespread expansion of the pilot policies, providing robust support for the development of IGG across all regions.

Second, address the locational heterogeneity caused by differences in institutional environments by implementing a regional coordination strategy that emphasizes both institutional strengthening and capacity transplantation. The study finds that the policy effects are more significant in eastern regions with mature institutional systems. Therefore, for key central and western cities such as Luoyang and Xiangyang, as well as regions with weak institutional foundations, focused efforts should be made on institutional capacity building and transplantation. It is recommended to systematically refine the mature regulations of eastern regions in areas such as green finance and the realization of ecological product value, forming standardized policy toolkits. Through cross-regional cadre exchanges, dispatched expert teams, and similar methods, assistance should be provided to local areas for institutional grafting and localized adaptation to quickly bridge institutional environment gaps and reduce effect dissipation during policy implementation.

Third, design industrial transformation pathways that break lock-in effects and foster ecological diversification in response to characteristic heterogeneity caused by differences in resource endowments. The research confirms that the resource curse effect significantly constrains the policy responsiveness of resource-based cities like Yulin and Ordos. For such cities, specialized interventions are needed to break path dependency. It is recommended to establish a national-level green transition fund for resource-based cities, prioritizing support for cultivating successor industries such as renewable energy and new materials. Additionally, the weight of non-resource industries' economic contribution and employment absorption in performance assessments should be substantially increased to fundamentally shift their development model from resource dependence to innovation-driven growth.

Fourth, construct a technology diffusion system centered on major-sized cities to drive the upgrading of small and medium-sized cities, addressing scale heterogeneity caused by differences in industrial structure. The research shows that major-sized cities, leveraging their advanced, knowledge-intensive industrial structures, can more efficiently absorb and translate policy dividends. Therefore, emphasis should be placed on utilizing the industrial and knowledge advantages of regional central cities like Chengdu and Wuhan, as well as advanced manufacturing base cities like Suzhou and Ningbo, to support their establishment of green technology open-source platforms and regional technology transfer centers. By establishing targeted collaboration mechanisms, these cities should be encouraged to output suitable technological solutions and share data and innovation resources with small and medium-sized cities that have solid manufacturing foundations, such as Wuhu, Zhuzhou, and Liuzhou, based on their own industrial bases. This transforms the industrial structure advantages of major-sized cities into practical drivers for regional coordinated development, effectively promoting the green industrial upgrading of small and medium-sized cities.

Fifth, strengthen multi-dimensional collaborative governance to optimize the mediating transmission pathways of "technology-organization-environment." The research confirms that the "dual pilot" policy primarily drives IGG through three major dimensions and six pathways: promoting R&D investment and technological innovation diffusion, enhancing human capital structure and optimizing industrial structure, and synergizing formal and informal environmental regulations. This requires policy implementation to be systematically integrated, avoiding advancement in a single dimension. Specifically, at the technological level, while ensuring sustained investment in R&D resources, it is essential to simultaneously construct efficient and collaborative technology transfer networks and digital public service systems, focusing on bridging the gaps in technology access and application capabilities among different cities. At the organizational level, talent development policies should be deeply aligned with local industrial green transformation strategies. Customized high-end talent attraction and cultivation plans should serve the upgrade needs of local leading industries, creating a mutually reinforcing pattern between human capital enhancement and industrial structure optimization. At the environmental level, governance methods should be innovated by combining mandatory regulations and standards with flexible, diverse social incentive mechanisms. By improving environmental information disclosure, promoting green consumption concepts, and broadening public supervision channels, a green development ecosystem that generates both binding force and endogenous motivation can be constructed. Through this multi-dimensional, systematic governance model, the entire process from policy formulation to effectiveness can be effectively integrated, ensuring that the core efficacy of driving IGG is consolidated and amplified.

7.3 Shortcomings and outlook

The following are the limitations of this paper: First, while this analysis uses panel data from 266 Chinese cities at the prefecture level and above from 2006 to 2022 as thoroughly as possible due to data availability constraints, future research could broaden the scope to include cross-national data for international comparisons. Second, the paper only focuses on the synergistic effects of innovation-driven policies and does not account for parallel policy combinations from other categories. A more thorough policy mix approach could be used in future research to evaluate the interplay between various tools. Third, based on the TOE theoretical perspective, this paper examines the impact of the innovation-driven "dual pilot" policy on urban IGG. To better understand the "black box" of mechanisms by which the "dual pilot" policy affects IGG, future studies may include other mediating or moderating variables.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

WL: Methodology, Software, Writing – review and editing, Visualization, Formal Analysis, Writing – original draft. MK: Resources, Writing – review and editing, Conceptualization, Validation. YC: Resources, Project administration, Investigation, Writing – review and editing, Funding acquisition.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2026.1735611/full#supplementary-material.

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