

Exploring Dynamic Pathways of Green Technology Innovation Efficiency in Provincial Regions of China

Badanie dynamicznych ścieżek efektywności innowacji w zakresie technologii ekologicznych w regionach prowincjonalnych w Chinach

Jinyu Wei¹, Juan Tan^{2*}

School of Management, Tianjin University of Technology, Tianjin 300384, China

¹*E-mail: weijinyu@tjut.edu.cn*

^{2*}*E-mail (Corresponding Author): tanjuan@stud.tjut.edu.cn*

Abstract

The efficiency of green technology innovation functions as a fundamental catalyst for realizing the synergy between innovation-driven development and ecological transformation, which is essential for achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). This study assesses green technology innovation efficiency across 30 Chinese provinces from 2013 to 2024 using the Data Envelopment Analysis (DEA) model. It constructs an analytical framework that integrates institutional settings, industrial structure, and market environment, and applies dynamic Qualitative Comparative Analysis (QCA) to examine the configurational effects of these factors on green technology innovation efficiency. Additionally, the Kruskal-Wallis rank sum test is employed to investigate spatial disparities in the configurational coverage at the provincial level. To address the temporal heterogeneity arising from events such as the COVID-19 pandemic, this study employs a dynamic QCA approach that captures both between-group and within-group variations across different time periods. The results indicate that no single factor constitutes a necessary condition for high green technology innovation efficiency; instead, three distinct pathways are identified as equally effective. Moreover, significant regional differences are observed in the configurational distribution of green technology innovation efficiency across the eastern, central, and western regions of China. These findings provide practical implications for policymakers seeking to advance China's sustainable development agenda through differentiated regional innovation strategies. This paper presents a multidimensional analytical framework and utilizes dynamic QCA to offer a comprehensive examination of complex causal relationships.

Key words: green technology innovation efficiency, Sustainable Development Goals, institutional setting, industrial structure, market consumption demand, Dynamic QCA

Streszczenie

Efektywność innowacji w zakresie zielonych technologii stanowi fundamentalny katalizator synergii między rozwojem opartym na innowacjach a transformacją ekologiczną, co jest niezbędne do osiągnięcia Celów Zrównoważonego Rozwoju ONZ (SDGs), w szczególności SDG 9 (Przemysł, Innowacje i Infrastruktura), SDG 12 (Odpowiedzialna Konsumpcja i Produkcja) oraz SDG 13 (Działania na rzecz klimatu). W niniejszym artykule dokonano oceny efektywności innowacji w zakresie zielonych technologii w 30 chińskich prowincjach w latach 2013–2024, wykorzystując model analizy danych (DEA). W badaniu skonstruowano ramy analityczne integrujące uwarunkowania instytucjonalne, strukturę przemysłową i otoczenie rynkowe, a także zastosowano dynamiczną jakościową analizę porównawczą (QCA) w celu zbadania wpływu konfiguracyjnego tych czynników na efektywność innowacji w zakresie zielonych technologii. Dodatkowo, do zbadania różnic przestrzennych w zakresie pokrycia konfiguracyjnego na poziomie prowincji zastosowano test sumy rang Kruskala-Wallisa. Aby uwzględnić heterogeniczność czasową wynikającą z wydarzeń takich jak pandemia COVID-19, w niniejszym badaniu zastosowano dynamiczne podejście QCA, które uwzględnia zarówno zmienność międzygrupową, jak i wewnątrzgrupową w różnych okresach. Wyniki wskazują, że żaden pojedynczy czynnik nie stanowi warunku koniecznego dla wysokiej

efektywności innowacji w zakresie zielonych technologii; zamiast tego zidentyfikowano trzy odrębne ścieżki jako równie skuteczne. Co więcej, zaobserwowano istotne różnice regionalne w rozkładzie konfiguracyjnym efektywności innowacji w zakresie zielonych technologii w regionach wschodnich, centralnych i zachodnich Chin. Wyniki te mają praktyczne implikacje dla decydentów politycznych dążących do realizacji chińskiego programu zrównoważonego rozwoju poprzez zróżnicowane regionalne strategie innowacji. Niniejszy artykuł przedstawia wielowymiarowe ramy analityczne i wykorzystuje dynamiczne QCA do kompleksowej analizy złożonych związków przyczynowo-skutkowych.

Słowa kluczowe: efektywność innowacji w zakresie technologii zielonych, Cele Zrównoważonego Rozwoju, otoczenie instytucjonalne, struktura przemysłowa, popyt konsumpcyjny na rynku, Dynamiczne QCA

1. Introduction

As globalization and industrialization advance, human society is confronted with unprecedented environmental and resource-related challenges. The conventional model of economic growth model, characterized by substantial resource consumption and significant environmental degradation, is increasingly deemed unsustainable (Song et al., 2024). In response to these global challenges, the United Nations adopted the 2030 Agenda for Sustainable Development in 2015, which encompasses 17 Sustainable Development Goals (SDGs) aimed at addressing poverty, inequality, climate change, environmental degradation, and promoting prosperity and peace (Lin, 2024). Among these goals, SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) are particularly relevant to the pursuit of green technology innovation, as they emphasize the importance of building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation while ensuring sustainable consumption and production patterns and taking urgent action to combat climate change. Consequently, green technology innovation (GTI) is widely recognized as a crucial mechanism for achieving harmonious development across economic, social, and environmental dimensions (Miao et al., 2024). Green innovation not only facilitates the efficient utilization of resources and the clean transformation of energy but also propels the optimization and upgrading of the industrial structures, thereby providing robust support for addressing climate change and fulfilling sustainable development objectives. Specifically, GTI contributes to SDG 7 (Affordable and Clean Energy) by promoting clean energy technologies, SDG 8 (Decent Work and Economic Growth) by fostering green jobs and sustainable economic growth, and SDG 11 (Sustainable Cities and Communities) by enabling the development of sustainable urban infrastructure (OECD, 2011). This is particularly significant in China, the world's largest energy consumer and carbon emitter, where GTI holds strategic significance for realizing the nation's goals of reaching carbon peak and carbon neutrality (Bian & Luo, 2025). China's commitment to achieving carbon neutrality by 2060 directly aligns with the global pursuit of SDG 13, and enhancing green technology innovation efficiency is instrumental in meeting these ambitious targets. However, the advancement and implementation of GTI encounter numerous obstacles, including technological immaturity, low market acceptance, high research and development costs, and inadequate policy support (Cheng et al., 2024). Furthermore, significant disparities in economic development, resource endowments, and technological capabilities across different regions exacerbate the regional imbalances in green innovation efficiency (Sun et al., 2024). These regional disparities pose challenges to achieving SDG 10 (Reduced Inequalities) within the context of sustainable development, as uneven distribution of innovation resources may lead to widening gaps between developed and underdeveloped regions. Therefore, a comprehensive analysis and understanding of the various factors affecting regional green innovation efficiency are of essential for formulating effective policy measures and promoting balanced development of technological innovation.

The drivers of green technological innovation efficiency (GTIE) can be systematically decomposed across firm, policy, market, and socio-cultural strata to facilitate the identification and interpretation of influencing mechanisms. At the corporate level, the principal determinants include research and development (R&D) expenditure, human-capital endowment, environmental, social and governance (ESG) performance, market demand for eco-products, and foreign direct investment (FDI). R&D outlays constitute the fundamental input for technological innovation, directly affecting the generation of new knowledge and the incremental improvement of existing technologies (Li et al., 2024). The educational attainment, professional competencies and innovative orientation of employees exert a decisive influence on the green-innovation capability of enterprises. ESG-related managerial practices strengthen corporate reputation and competitive positioning in green-technology segments (Wang & Sun, 2022). Consumer preference for environmentally friendly goods creates demand-pull incentives that induce firms to introduce greener solutions, while the presence of foreign affiliates transmits advanced technologies and managerial know-how, thereby accelerating the green-innovation diffusion of domestic firms (Liang et al., 2025).

At the policy and regulatory level, environmental mandates, fiscal subsidies, tax incentives and technology-innovation programmes constitute the key levers. Command-and-control instruments such as emission standards and environmental legislation oblige enterprises to adopt cleaner production processes (Guo et al., 2023; Luo et al.,

2021). Governmental fiscal support lowers the private cost of innovation, stimulates R&D investment and facilitates the commercialisation of green technologies (Philipp, 2016). Public R&D schemes that combine direct funding with tax concessions enhance both the creation and the deployment of eco-innovations (Ayla & Cihan, 2025). These policy instruments are consistent with SDG 17 (Partnerships for the Goals), which emphasizes the importance of multi-stakeholder partnerships and policy coherence for sustainable development. Market and industry-level factors, including industrial-structure adjustment and competitive dynamics, likewise exert significant influence. The continual upgrading of industrial composition – particularly the shift toward high-technology and service-oriented activities – generates new technological opportunities and enlarges the domain for green-innovation applications (Wang et al., 2022). Intensified competitive pressures within industries compel firms to differentiate themselves through eco-innovation, thereby reinforcing the market-driven momentum for greener technologies. Finally, socio-cultural determinants play a pivotal role. Elevated public environmental awareness and societal support for sustainable development cultivate an institutional climate that legitimises green-innovation activities and expands market demand for eco-friendly solutions (Shen et al., 2021).

The investigation of GTIE constitutes an interdisciplinary and multi-methodological domain, integrating theories and practices from economics, management, environmental science, and various other fields (Yuan et al., 2024). Researchers have employed a diverse array of both quantitative and qualitative methodologies to evaluate and analyze the efficiency of green technology innovation. Predominant quantitative approaches include Data Envelopment Analysis (DEA, Abbasi et al., 2022), Stochastic Frontier Analysis (SFA, Battese & Coelli, 1995), and the Synthetic Control Method. DEA is a non-parametric technique for assessing relative efficiency within production processes and is frequently used to evaluate technological innovation efficiency. Conversely, SFA incorporates random errors and inefficiency behaviors, thereby offering a more adaptable framework for efficiency evaluation. The Synthetic Control Method evaluates the effects of policy interventions by constructing a virtual control group, making it suitable for assessing the impacts of specific technology innovation policies. Qualitative methodologies encompass case studies, focus groups, and interviews. In recent years, the emergence of mixed-methods research has prompted scholars to amalgamate the strengths of both quantitative and qualitative approaches, thereby facilitating a more holistic research perspective. For instance, the outcomes derived from DEA and SFA can be integrated with insights from case studies to corroborate and enhance the conclusions drawn from efficiency evaluations. Additionally, System Dynamics (SD) and Agent-Based Models (ABM) are employed to simulate the dynamic processes and complex systems associated with green technology innovation. These models are adept at capturing feedback loops and nonlinear relationships inherent in technological innovation processes, thus providing valuable tools for comprehending long-term trends and potential ramifications of green technology innovation (Tone & Tsutsui, 2009; Fang et al., 2019). Lastly, Qualitative Comparative Analysis (QCA), as a novel research methodology, is particularly effective in examining the combined effects of multiple conditional factors (Ragin, 2008). QCA enables researchers to identify various combinations that contribute to high-efficiency green technology innovation, thereby offering a fresh perspective for the development of effective innovation strategies. Despite the extensive research conducted on Green Technology Innovation Efficiency (GTIE) within the existing literature, several issues persist. Firstly, empirical attribution derived from normative discourse lacks empirical substantiation. Secondly, empirical attribution that employs linear regression tends to focus on the *net effect* of individual variables, thereby neglecting the diverse collaborative pathways that contribute to green technology innovation efficiency, which precludes the possibility of offering differentiated pathways. This approach often relies on regression analysis while overlooking the dependent relationships inherent in causality. Thirdly, most existing studies fail to explicitly connect green technology innovation efficiency with the broader sustainable development framework, particularly the SDGs, thereby limiting the policy relevance of their findings for national and international sustainability agendas. Lastly, although some studies have employed fuzzy qualitative comparative analysis (fsQCA), their application is restricted to cross-sectional data and primarily emphasizes consistency, thereby failing to explore coverage and the temporal dynamics of component interactions. Moreover, the temporal heterogeneity introduced by significant events such as the COVID-19 pandemic necessitates analytical approaches that can capture dynamic variations across different periods. Consequently, there is a pressing need for further research to elucidate the evolving patterns of green technology innovation efficiency across various regions in China over time from a configurational perspective.

The primary contributions of this article are threefold. First, it introduces a multidimensional analytical framework that encompasses *institutional settings – industrial structure – market environment*, which may provide a more comprehensive and nuanced understanding of green technology innovation efficiency. Second, the article employs the dynamic Qualitative Comparative Analysis (QCA) method to investigate the factors influencing green technology innovation efficiency. This method enables researchers to examine the synergistic effects of multiple factors, thereby facilitating a deeper comprehension of complex causal relationships. Third, this study explicitly situates the analysis of green technology innovation efficiency within the context of the United Nations Sustainable Development Goals, thereby bridging the gap between regional innovation studies and the global sustainable development agenda.

2. Theoretical framework

This study utilizes provincial panel data to investigate the pathways for enhancing the efficiency of regional green technology innovation within the context of sustainable development. The theoretical foundation of this research is grounded in the understanding that green technology innovation serves as a critical mechanism for achieving multiple SDGs simultaneously. Specifically, improvements in GTIE can contribute to SDG 9 by fostering sustainable industrialization, SDG 12 by promoting resource efficiency and cleaner production, and SDG 13 by reducing carbon emissions and mitigating climate change impacts (Sachs et al., 2019). Consequently, an analytical framework is established, focusing on three key dimensions: institutional arrangements, industrial composition, and market factors.

(1) A comprehensive examination of the institutional dimension reveals significant influences. Initially, government-imposed environmental regulations and fiscal policies constitute the foundational elements of the institutional framework that supports green technological innovation (Zhang et al., 2021). Environmental regulations create compliance pressures for enterprises by establishing emission standards and pollution control mandates, which not only elevate operational costs but also incentivize businesses to innovate technologically in order to reduce expenses and improve competitiveness (Rennings, 2000). Furthermore, fiscal policies, such as research and development subsidies and tax incentives, can effectively lower the costs associated with innovation for enterprises, thereby enhancing the attractiveness of green technological initiatives (Liao et al., 2024). Additionally, fiscal decentralization empowers local governments with increased autonomy, allowing them to devise green innovation policies that are better suited to the specific economic development levels and industrial characteristics of their regions. By optimizing fiscal expenditure structures and augmenting support for the research, development, and dissemination of green technologies, local governments can significantly advance the growth of the local green economy (Zhang et al., 2022; Wang et al., 2022). These institutional arrangements are consistent with SDG 16 (Peace, Justice and Strong Institutions), which emphasizes the importance of effective, accountable and inclusive institutions at all levels.

(2) A comprehensive examination at the level of industrial structure reveals that as the industrial framework undergoes optimization and enhancement, traditional sectors progressively shift towards more sustainable and efficient production methodologies. This industrial transformation directly supports SDG 9, which calls for upgrading infrastructure and retrofitting industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies. In this transition, it is imperative for both governmental bodies and enterprises to persistently investigate novel green technologies and innovative business models in order to align with evolving market demands and environmental regulations. The process of industrial upgrading encompasses not only technological advancements but also significant transformations in management practices, marketing strategies, and supply chain dynamics (Zhou et al., 2023). In the pursuit of fostering green innovation, local governments should prioritize inter-industry collaboration and partnerships. By instituting mechanisms such as industry alliances and innovation platforms, they can promote the exchange of knowledge and facilitate the transfer of technology across various sectors, thereby accelerating the dissemination and implementation of green technologies. Furthermore, the phenomenon of green knowledge spillover among provinces warrants attention; by enhancing regional cooperation and exchange, the optimal allocation and effective utilization of resources dedicated to green innovation can be advanced (Ma & Cao, 2022).

(3) An expanded analysis at the market environment level reveals that market demand serves as a significant catalyst for green technological innovation. As consumer awareness regarding health, environmental sustainability, and ecological protection intensifies, the demand for environmentally friendly products correspondingly rises. This consumer-driven transformation aligns with SDG 12, which promotes sustainable consumption and production patterns and encourages companies to adopt sustainable practices and integrate sustainability information into their reporting cycles. Consequently, businesses must remain attuned to market trends and develop green products that align with consumer preferences in order to secure a competitive advantage (Horbach et al., 2012). Furthermore, the facilitation of foreign investment not only attracts foreign direct investment but also promotes the transfer of technology and managerial expertise. The spillover effects associated with foreign direct investment provide local enterprises with valuable opportunities for learning and imitation, thereby expediting their technological innovation and industrial advancement. Concurrently, local enterprises, confronted with international competitive pressures, must continuously enhance their research and development capabilities and innovation capacities to effectively navigate the competitive landscape of the global market (Liang et al., 2025).

(4) Equifinality and a Configural Perspective. This research will employ a configural perspective to investigate the concept of equifinality across various combinations of factors (see Figure 1). Specifically, it aims to understand how identical outcomes in green innovation can be attained under diverse institutional environments, industrial frameworks, and market conditions through varying combinations of factors. This endeavor necessitates a comprehensive literature review and theoretical analysis of existing studies, as well as empirical research that elucidates the underlying logic and mechanisms of action associated with different factor combinations through case studies and comparative analyses. The configurational approach adopted in this study recognizes that achieving

sustainable development outcomes, including those related to green technology innovation, may follow multiple equally effective pathways, which is consistent with the integrated and indivisible nature of the SDG framework that acknowledges the interconnections among different goals and targets.

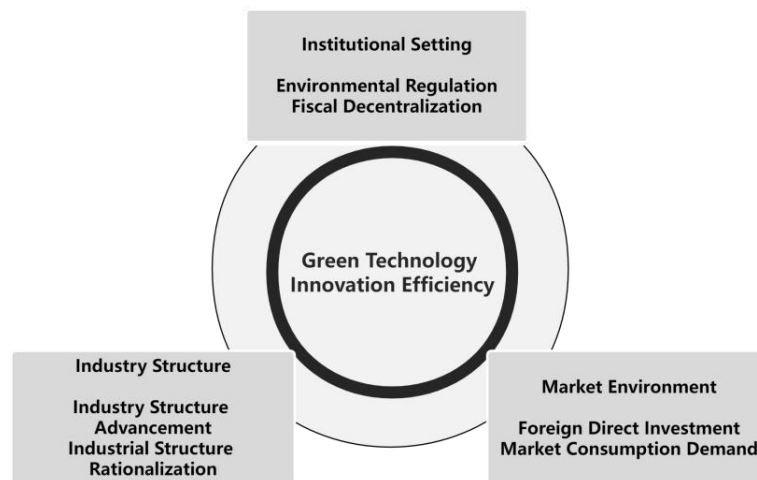


Figure 1. Analysis framework of regional green technology innovation efficiency

3. Research methods and data

3.1. Dynamic QCA

The predominant body of research concerning the enhancement of Green Technology Innovation Efficiency (GTIE) and its determinants relies heavily on econometric analyses that focus on independent variables, unidirectional linear relationships, and causal symmetry (Jiang et al., 2022; Zhou & Wang, 2022). However, it is essential to recognize that multiple conjunctural causation arises from the interdependence and interaction of various causal factors (Rihoux & Ragin, 2009). This study aims to investigate the intricate and diverse mechanisms that underpin GTIE across different regions in China from a configurational perspective, employing Qualitative Comparative Analysis (QCA) grounded in set theory. This approach is warranted for several reasons. Firstly, traditional econometric methodologies fall short in capturing the complex causal relationships, such as the interdependence among independent variables, when analyzing the independent or paired interactions of factors like environmental regulations, industrial institutions, and market demand. The QCA method is more adept at exploring the mechanisms through which various factors influence the efficacy of regional green technology innovation from a comprehensive viewpoint. Secondly, the varied pathways to enhancing GTIE across different provinces indicate that multiple equifinal causal chains can yield the same outcome. Traditional econometric approaches tend to describe the influence on the dependent variable through mediating and moderating variables, elucidating the variation of the dependent variable via the substitution or accumulation relationship of independent variables (Du et al., 2021). In contrast, the QCA technique is capable of identifying complete equivalence among distinct configurations of antecedent conditions and can elucidate results that are not mutually exclusive (Fiss, 2011). Consequently, the QCA method is more appropriate for identifying pathways to improve GTIE.

The increasing focus on temporal effects (Landmarks, 1989) has raised concerns regarding the validity of static Qualitative Comparative Analysis (QCA), as it does not adequately address the sequential and dynamic nature of antecedent conditions. Time significantly influences the outcomes of dynamic research. Thus, integrating the temporal dimension into QCA analysis is beneficial for advancing dynamic configuration theory (Du et al., 2021). GTI represents a continuous process that unfolds over time, and a singular cross-sectional configuration fails to capture the interactive relationship between the trajectory of GTIE improvement and time. Moreover, the study period from 2013 to 2024 encompasses significant temporal heterogeneity, including the COVID-19 pandemic (2020–2022), which substantially disrupted economic activities, industrial production, and innovation processes across China's provinces. The pandemic period witnessed varying degrees of lockdowns, supply chain disruptions, and shifts in government priorities toward public health, which may have differentially affected green technology innovation across regions (Jin et al., 2021). To account for this temporal heterogeneity, this study employs dynamic QCA analysis, which assesses consistency across between-group, within-group, and pooled dimensions, thereby capturing variations that arise from different time periods and enabling a more robust understanding of the configurational relationships. Consequently, this study employs dynamic QCA analysis and Enhanced Criteria Analysis (ESA) utilizing RStudio software to explore the configurational relationships influenced by temporal effects (Garcia-Castro & Arino, 2016). Unlike traditional QCA, dynamic QCA assesses consistency across between, within

and pooled dimensions. The concept of consistency distance is utilized to quantify the extent of change in consistency over time and across various case dimensions (Chang, 2025).

3.2. Data and variables

In light of data accuracy and availability, the study employs provincial-level panel data covering thirty Chinese provinces for the period 2013–24, with Tibet, Hong Kong and Macao excluded. The dataset is compiled from the CSMAR database, China Statistical Yearbook and China Energy Statistical Yearbook.

3.2.1 Outcome and condition variables

The outcome variable is green technology innovation efficiency (GTIE). Provincial-level GTIE for 30 Chinese provinces from 2013 to 2024 is estimated with a non-radial and non-angular super-slacks-based measure (SSBM) that accommodates undesirable outputs; the corresponding indicator system is presented in Table 1. The measurement of GTIE is designed to capture the sustainability dimension of innovation by incorporating both desirable outputs (technological, economic, and ecological benefits) and undesirable outputs (environmental pollutants), thereby reflecting the core principle of SDG 12 that emphasizes decoupling economic growth from environmental degradation. Inputs consist of human resources, capital, and energy. Human resources are measured by full-time equivalent R&D personnel (Wang et al., 2021b), capital input by intra-mural R&D expenditure (Li et al., 2024), and energy input by regional electricity consumption (Zeng et al., 2022). Desirable outputs comprise technological, economic, and ecological dimensions: technological output is proxied by the number of green patent applications; economic output is reflected by the revenue from new-product sales; ecological output is represented by the green coverage rate of built-up areas (Shen et al., 2021). Undesirable outputs include industrial sulphur-dioxide emissions, industrial wastewater discharge, and the generation of general industrial solid waste (Chang, 2025). The inclusion of undesirable outputs in the efficiency measurement aligns with the SDG framework's emphasis on reducing pollution (SDG 11 Target 11.6) and substantially reducing waste generation through prevention, reduction, recycling and reuse (SDG 12 Target 12.5).

Table 1. The evaluation index system of GTIE

Category	Measurement	SDG Alignment	Reference
Input			
Human resources	Full-time equivalent R&D personnel	SDG 4, SDG 8	Wang et al., 2021b
Capital	Internal R&D expenditure	SDG 9	Li et al., 2024
Energy	Regional power consumption	SDG 7	Zeng et al., 2022
Output-desirable			
Technological production	Number of regional green patent applications	SDG 9	Shen et al., 2021
Economic benefit	New product sales income	SDG 8	
Ecological benefit	Green covering rate of region's built-up areas	SDG 11, SDG 15	
Output-undesirable			
Pollutions	Industrial sulfur dioxide emissions	SDG 3, SDG 13	Chang, 2025
	Industrial wastewater emissions	SDG 6, SDG 14	
	General industrial solid waste generation	SDG 12	

The conditioning variables are examined at three hierarchical levels: institutional framework, industrial composition and market setting. Within the institutional dimension, environmental regulation and fiscal decentralisation are considered. The intensity of environmental regulation is measured by the ratio of completed investment in industrial pollution control to the value-added of the secondary sector (Xie et al., 2017). This indicator reflects governmental commitment to environmental protection, which is a key component of SDG 12 and SDG 13. Fiscal decentralisation, motivated by carbon-peaking and carbon-neutrality objectives and aimed at correcting market failures for green development, is assessed on the expenditure side (Mu & Yang, 2023).

Industrial-structure conditions comprise advancement and rationalisation. Advancement of industrial structure (AIS) is captured by the ratio of tertiary-sector value-added to secondary-sector value-added, reflecting the relative weight of the tertiary sector in the national economy (Wang et al., 2021a). Industrial upgrading toward service-oriented and knowledge-intensive sectors is consistent with SDG 9 Target 9.2, which emphasizes promoting inclusive and sustainable industrialization. Rationalisation of industrial structure (RIS) is proxied by the Theil index, which indicates regional industrial concentration and the efficient use of resource endowments (Wang et al., 2021a). The Theil index is computed using regional output values and labour inputs across the three industrial sectors, as specified in the following formula.

$$RIS = \sum_{i=1}^n \left(\frac{Y_i}{Y} \right) \ln \left(\frac{Y_i/L_i}{Y/L} \right) \quad (1)$$

Where, Y represents the output value; L denotes employment, and i ($i=1,2,3$) indicates three industries. The Theil index is a reversal indicator, the lower the index value, the greater the degree of RIS.

Market conditions can be exemplified by the degree of market openness and market consumption demand (MCD). Foreign Direct Investment (FDI) is quantified using its natural logarithm (Liang et al., 2025), while the per capita disposable income of urban residents serves as a metric for estimating market consumption demand. Higher market consumption demand for green products reflects growing consumer awareness of sustainability issues, which is central to achieving SDG 12's objective of ensuring sustainable consumption patterns.

3.2.2. Calibration

This article undertakes a unified calibration of the data for subsequent study of between group, within group, and pooled consistency and coverage, drawing on current theories and research. The direct calibration method is used to set the 95%, 50% and 5% quantiles as calibration anchors, signifying fully in membership, intermediate, and fully out membership, respectively, based on the numerical features of variables (Guedes et al., 2016). The calibration anchor points are shown in Table 2.

Table 2. Calibration

Variable		Fully in	Intermediate	Fully out
Outcome	GTIE	1.693	0.352	0.124
Conditions	ER	0.68	0.164	0.022
	FD	0.966	0.891	0.844
	AIS	3.061	1.315	0.871
	RIS	0.601	0.133	0.019
	FDI	9.625	7.074	4.455
	MCD	10.94	10.16	9.606

4. Data analysis and discussion

4.1. Analysis of the necessity of individual conditions

Prior to conducting a comprehensive analysis of conditional configurations, it is imperative to evaluate the necessity of each individual condition (refer to Table 3). An antecedent condition is deemed necessary for the outcome if it exhibits a consistency level exceeding 0.9, signifying that the condition is invariably present when the outcome occurs (Ragin, 2008; Schneider et al., 2009). In the context of Qualitative Comparative Analysis (QCA) utilizing panel data, several indicators are employed to assess the necessity of condition variables, including pooled consistency (POCONS), between consistency (BECONS), within consistency (WICONS), pooled coverage (POCOV), between coverage (BECOV), and within coverage (WICOV). A POCONS value is considered highly accurate and can serve as a determinant when the consistency distance is below 0.1 (Garcia-Castro & Arino, 2016). Conversely, if the consistency distance exceeds 0.1, further investigation into the necessity of the condition is warranted. The analysis reveals that the consistency distances are below 0.1, and the POCONS values are less than 0.9, indicating that these factors do not qualify as necessary for the outcome variable (GTIE), as illustrated in Table 3. This finding suggests that achieving high GTIE and advancing toward sustainable development objectives cannot rely on any single factor alone, but rather requires the synergistic combination of multiple conditions – a conclusion that aligns with the integrated and indivisible nature of the SDG framework.

Table 3. Necessity analysis

Condition	High GIE				Non-high GIE			
	POCONS	POCOV	BECONS distance	WICONS distance	POCONS	POCOV	BECONS distance	WICONS distance
ER	0.544	0.547	0.085	0.075	0.703	0.78	0.062	0.05
~ER	0.781	0.704	0.05	0.041	0.592	0.589	0.096	0.072
FD	0.739	0.719	0.011	0.067	0.564	0.605	0.033	0.086
~FD	0.594	0.553	0.015	0.084	0.738	0.757	0.024	0.069
AIS	0.692	0.745	0.067	0.055	0.528	0.626	0.087	0.072
~AIS	0.652	0.559	0.049	0.066	0.785	0.738	0.037	0.05
RIS	0.554	0.609	0.095	0.081	0.622	0.754	0.049	0.057
~RIS	0.776	0.651	0.05	0.047	0.677	0.626	0.05	0.052
FDI	0.766	0.702	0.031	0.057	0.594	0.6	0.095	0.08
~FDI	0.564	0.557	0.059	0.08	0.705	0.768	0.058	0.058
MCD	0.753	0.749	0.065	0.046	0.526	0.577	0.089	0.078
~MCD	0.575	0.524	0.07	0.074	0.772	0.775	0.074	0.047

Note: ~ means the absence of.

To summarize, none of the individual antecedents meet the necessary conditions to affect high or non-high GTIE, hence more research is needed to investigate the impact of conditional configuration on the GTIE enhancement path.

4.2. Sufficiency analysis of conditional configuration

The foundation of the Qualitative Comparative Analysis (QCA) method lies in configuration analysis, which aims to examine how various combinations of antecedent conditions influence outcomes. A consistency threshold of 0.75 is established to ascertain sufficiency (Schneider & Wagemann, 2013). In this study, the truth table is organized using a consistency threshold of 0.9, a frequency threshold of 2, and a PRI threshold of 0.75 (Du & Jia, 2017), ultimately encompassing 65 cases. Subsequently, an enhanced standard analysis is conducted. During the contrarian case analysis, any conflicting simplifying hypotheses are dismissed. Additionally, due to the disparities in resource endowments across regions concerning Green Technology Innovation Efficiency (GTIE), it is not feasible to uniformly assess the impact of antecedents on outcomes; therefore, the direction of influence remains indeterminate, with all conditions categorized as either *presence or absence*. Ultimately, the analysis yields enhanced parsimonious, intermediate, and complex solutions. This study aims to delineate the fundamental and ancillary conditions by concentrating on the improved intermediate solution, which is supported by the enhanced parsimonious solution. The results of the configuration analysis are presented in Table 4, which encompasses three solutions designated as N1-N3. These configurations can be further distilled into two models: one characterized by multi-core pathways (N1 and N2) and the other defined by pathways influenced by institutional-market peripheral conditions (N3).

4.2.1 Aggregated results

The pooled coverage (POCOV) is 0.601, the pooled consistency (POCONS) is 0.935, and the pooled PRI is 0.877, as shown in Table 4. For individual configurations, the consistency distances between and within groups are smaller than 0.1. This finding indicates that these three pathways remain stable across different time periods, including before, during, and after the COVID-19 pandemic, suggesting their robustness in guiding sustainable development strategies despite external shocks. This suggests that these three paths are the key strategies for enhancing GTIE.

Paths driven by multi cores (solutions N1 & N2) reflect combinations of the existence and absence of institutional, industrial and market attributes for high GTIE for occur. The conditions FD, AIS, FDI and MCD are core constructs that emphasize the significance of these components. In particular, regardless of FDI, the combination of high FD, high MCD, AIS and RIS, and the absence of high ER, results in high GTIE (solution N1). To that purpose, the presence of FD, AIS, RIS and MCD can be paired with high FDI (solution N2) or the absence of ER (solution N1) to create high GTIE. Path driven by the institutional-market peripheral conditions (solution N3), on the other hand, if none of the factors are core factors, the presence of high FD, FDI and MCD, the absence of ER and RIS, and regardless of AIS, can produce the same result.

Table 4. Configurations for achieving high GIE

Solutions	N1	N2	N3
Institutional Setting			
ER	⊗		×
FD	★	★	★
Industrial Structure			
AIS	★	★	
RIS	●	●	×
Market Environment			
FDI		★	●
MCD	★	●	●
Consistency	0.947	0.923	0.939
PRI	0.851	0.866	0.829
Coverage	0.315	0.352	0.401
Unique coverage	0.039	0.067	0.199
BECONS distance	0.018	0.014	0.012
WICONS distance	0.022	0.028	0.02
Pooled PRI	0.877		
POCONS	0.935		
POCOV	0.601		

Note: ★=core causal condition present; ⊗=core causal condition absent; ☆=peripheral condition present; ×=peripheral condition absent. Blank spaces indicate 'do not care'.

Beijing serves as a pertinent example of solution N1 and N3, exemplifying the fundamental characteristics associated with this approach. As the capital city, Beijing possesses a significant degree of fiscal autonomy, which facilitates investment in research and development of green technologies, thereby fostering green economic growth. Concurrently, the city is engaged in the optimization of its industrial structure, diminishing its dependence on industries that are both heavily polluting and energy-intensive, while simultaneously encouraging green innovation. Beijing's green development strategy directly contributes to multiple SDGs, including SDG 11 (Sustainable Cities and Communities) through its urban environmental improvement initiatives and SDG 13 (Climate Action) through its carbon reduction commitments. The rising environmental consciousness and increasing income levels among residents have led to a heightened market demand for green products, prompting businesses to enhance their investments in green technology innovation. Additionally, the Beijing municipal government has implemented policies aimed at promoting new energy vehicles and green buildings, which further stimulate green consumption. These initiatives are consistent with the principles of fiscal decentralization, an advanced industrial structure, and the prevailing market demand characteristic of solution N1 and N3. Jiangsu is characterized by a significant level of fiscal decentralization and a robust high-tech industry. Furthermore, it ranks among the leading provinces in China in terms of attracting foreign direct investment, housing a multitude of foreign-funded enterprises and research and development centers established by multinational corporations. The presence of these foreign entities has facilitated the influx of capital, as well as the introduction of advanced technologies and management practices, thereby fostering the advancement and innovation of local green technologies. Jiangsu's approach exemplifies the role of international cooperation and technology transfer emphasized in SDG 17 (Partnerships for the Goals). Consequently, the circumstances in Jiangsu serve as a pertinent illustration of solution N2.

In summary, the interplay of institutional frameworks, industrial configurations, and market conditions can facilitate elevated levels of Green Technology Innovation Efficiency (GTIE) through various mechanisms. The findings of this study indicate that, despite variations in resource endowments, specific regions can achieve high efficiency in green technology innovation by leveraging a combination of characteristics. Additionally, fiscal decentralization and market consumption demand significantly influence the distribution of factors across the three identified solutions. This phenomenon can be attributed to the proactive stance of local governments, which are dedicated to fostering sustainable regional economic development and are thus inclined to promote green technology innovation. Such governmental commitment can enhance the motivation for innovation among regional entities through financial constraints imposed by local budgets, ultimately leading to increased outputs in green technology innovation. Furthermore, it is observed that the impetus for regional green technology innovation in China is primarily driven by market demand rather than supply factors. Consequently, it is imperative for both governmental bodies and enterprises to remain attuned to fluctuations in market demand in their future endeavors related to green technology development. These findings have important implications for achieving SDG 12 (Responsible Consumption and Production), as they highlight the critical role of consumer demand in driving the transition toward sustainable production systems.

4.2.2. Heterogeneity analysis

This article examines the disparities in coverage among various groups to illustrate the regional distribution of cases that each configuration can account for. The analysis employs the Kruskal-Wallis rank sum test to assess whether significant differences exist in the coverage distribution of each configuration across the eastern, central, and western regions, thereby conducting a heterogeneity analysis. The findings indicate that the efficiency of green technology innovation in the eastern region is relatively stable, whereas the central and western regions exhibit an upward trend; however, pronounced regional disparities persist nationwide, characterized by a pattern of higher performance in the east compared to the west. These regional disparities reflect broader challenges related to SDG 10 (Reduced Inequalities), as uneven distribution of innovation resources and capabilities may exacerbate developmental gaps between regions. Notable regional differences are evident in the spatial distribution of cases that configurations 1-3 can elucidate. Specifically, configuration 1 encompasses cases from eastern coastal areas such as Guangdong, Shanghai, Beijing, and Zhejiang. Configuration 2 includes regions like Hunan and Hubei, while configuration 3 is represented by typical cases from Guizhou and Shaanxi. The underlying reasons for these disparities include the eastern region's superior economic foundation and more developed innovation system, which confer significant advantages in areas such as institutional environment, industrial structure, and market share. Conversely, the central and western regions, characterized by a weaker resource base, face relatively inadequate conditions for enhancing green technology innovation efficiency. Addressing these regional disparities is essential for China's pursuit of inclusive sustainable development, consistent with the sustainability principle of *leaving no one behind*.

4.2.3. Robustness check

This article utilizes multiple methodologies to conduct robustness testing for panel Qualitative Comparative Analysis (QCA). Initially, the consistency threshold is decreased from 0.9 to 0.8, which yields results that align with the original findings. Furthermore, the calibration method is modified by setting the full-in and full-out anchors to

the 85th and 15th percentiles, respectively, while maintaining the intermediate point constant. The resulting configuration remains largely consistent with the pre-existing configuration. Additionally, to address the potential impact of the COVID-19 pandemic on the robustness of findings, a supplementary analysis was conducted by separately examining the pre-pandemic period (2013-2019) and the pandemic and post-pandemic period (2020-2024). The results indicate that the core configurations remain stable across both periods, although some peripheral conditions show minor variations, confirming the robustness of the identified pathways to external shocks. Consequently, this approach demonstrates a significant degree of resilience.

5. Findings

The enhancement of green technology innovation efficiency (GTIE) is a complex process that is significantly shaped by the interactions among institutional, industrial, and market factors, alongside notable regional disparities. Prior research has produced varying conclusions regarding these influences. This study posits that fiscal decentralization serves as a more critical determinant than environmental regulation, which has identified as a missing conditional variable in the pathway to improving GTIE (see Table 4). Miao et al. (2024) assert that environmental policies are pivotal in moderating the green technology innovation process, particularly in relation to the carbon emission efficiency of high-energy-consuming manufacturing sectors. The heterogeneity analysis presented in this paper reveals that green technology innovation is more effective in the economically developed eastern regions, whereas Miao et al. (2024) contend that the impact of green technology innovation on carbon emission efficiency is especially pronounced in the central regions and among declining enterprises. Furthermore, the research conducted by Sun et al. (2024) highlights the significant role of market consumption demand in influencing the efficiency of industrial green technology innovation, while this study underscores the more substantial impact of industrial structural upgrading.

From a sustainable development perspective, the findings of this study contribute to the understanding of how different combinations of factors can advance multiple SDGs simultaneously. The identification of fiscal decentralization as a core condition in all three configurations suggests that empowering local governments with fiscal autonomy is crucial for promoting green innovation, which aligns with SDG 16's emphasis on effective and accountable institutions. The prominence of industrial structure advancement (AIS) in configurations N1 and N2 indicates that the transition from resource-intensive manufacturing to service-oriented and high-technology industries is essential for achieving the sustainable industrialization objectives outlined in SDG 9. Moreover, the significance of market consumption demand (MCD) in all configurations underscores the importance of fostering sustainable consumption patterns (SDG 12) as a driver of green innovation.

The pursuit of enhanced efficiency necessitates governmental intervention to address the externalities associated with technological innovation. This endeavor is inherently complex due to varied needs and capacities of industries across different geographical regions. It is imperative for the government to effectively respond to the diverse requirements of industrial advancement and the integration of both physical and institutional infrastructure, ensuring that these efforts are tailored to the specific conditions of each region. Acknowledging the limitations in available resources and implementation capabilities, the government must strategically and selectively allocate these resources. This selective approach is fundamental to government industrial policies, which seek to rationalize and promote industries in a manner that is attuned to regional disparities. The market theories proposed by Mises and Hayek suggest that the market operates as a voluntary system of human cooperation and serves as a cognitive instrument, with competition within the market facilitating the discovery and establishment of new opportunities for trade and collaboration. The most distinguishing characteristic of the market is its dynamism, which promotes change and innovation through the division of labor and specialization – key factors that drive innovation.

The effectiveness of market mechanisms is not universally applicable, as they are unable to address all issues or achieve optimal resource allocation, particularly in consideration of regional diversity. The profit-driven nature of market operations imposes certain limitations, thereby highlighting the necessity for government intervention through the implementation of industrial policies. Such policies should be designed with an awareness of the unique characteristics of regional economies, ensuring that the advantages of green technology innovation are distributed equitably across the nation, rather than being concentrated in developed regions.

To enhance the efficiency of green technology innovation, it is essential that the intrinsic mechanisms of the market and government interventions – such as environmental regulations, fiscal decentralization, and the strategic application of industrial policies – function collaboratively. Although these measures may vary, they ultimately share a common objective: to promote green technology innovation in a manner that is sensitive to regional disparities and supportive of sustainable and inclusive growth. The government's role is to coordinate this intricate interplay, ensuring that all regions are included in the transition towards a more sustainable and innovative future. This coordinated approach is essential for advancing China's progress toward the SDGs, particularly in ensuring that the benefits of green technology innovation contribute to poverty reduction (SDG 1), improved health outcomes (SDG 3), and climate action (SDG 13) across all regions of the country.

6. Conclusions and implications for sustainable development

This study, through thorough analysis and empirical investigation, has explored the impact of regional disparities on the efficiency of green technology innovation and has suggested specific strategies for improvement. The results of this study not only highlight the variations in green technology innovation efficiency among various regions but also pinpoint the critical factors influencing these disparities. Importantly, this research contributes to the broader understanding of how regional innovation systems can be optimized to advance the United Nations Sustainable Development Goals.

The theoretical contributions of this study are primarily manifested in three key areas: (1) the application of dynamic QCA to examine the pathways that enhance the green technology innovation efficiency. This approach takes into account the interplay of multiple factors, thereby enriching the existing body of literature and offering a more nuanced understanding of green technology innovation efficiency within complex systems. (2) Integration of regional disparities into the research framework concerning green technology innovation efficiency introduces a novel perspective for analyzing the performance and effects of technological innovation across diverse geographical and economic contexts. (3) The explicit connection between green technology innovation efficiency and the SDG framework provides a bridge between regional innovation studies and the global sustainable development agenda, demonstrating how improvements in GTIE can simultaneously advance multiple SDGs, including SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action).

From a managerial standpoint, this research provides several key insights: (1) Tailored innovation policies aligned with SDGs. It is essential for policymakers to acknowledge the variations in innovation resources, capabilities, and requirements across different regions, thereby developing tailored innovation policies that foster balanced advancements in green technology innovation efficiency across diverse areas. Such policies should be explicitly linked to specific SDG targets to ensure coherence with national and international sustainability commitments. (2) Integration of policy and market mechanisms. The findings underscore the significance of fiscal decentralization rather than environmental regulations alone in facilitating green technology innovation, suggesting that when crafting environmental policies, governmental bodies should incorporate market incentive mechanisms to enhance corporate innovation motivation. This approach is consistent with SDG 17's emphasis on multi-stakeholder partnerships and policy coherence. (3) Advancement of industrial clustering and regional integration. The study indicates that industrial structure advancement and rationalization positively influences the efficiency of green technology innovation; thus, it is imperative for the government to facilitate the optimal allocation of innovation resources and the broad dissemination of innovative outcomes by refining industrial organization and bolstering regional integration. These efforts should prioritize the transition toward sustainable industrialization as outlined in SDG 9. (4) Addressing regional inequalities. The significant regional disparities identified in this study highlight the need for targeted interventions in central and western regions to ensure that the benefits of green technology innovation are distributed equitably, consistent with SDG 10's objective of reducing inequalities within countries.

This study has several limitations that warrant acknowledgment. First, while the dynamic QCA approach captures temporal variations, the analysis does not fully isolate the specific effects of the COVID-19 pandemic on green technology innovation efficiency. Future research could employ more granular temporal analyses to examine how external shocks differentially affect various configuration pathways. Second, the SDG framework encompasses interconnections among multiple goals that extend beyond the scope of this study; future research could explore how green technology innovation efficiency contributes to additional SDGs, such as SDG 6 (Clean Water and Sanitation) and SDG 14 (Life Below Water). Third, this study focuses on provincial-level analysis within China; comparative studies across different countries could provide valuable insights into how diverse national contexts shape the pathways to sustainable green innovation.

Data availability

Data will be made on request.

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