# Configurational Pathways of Digital Empowerment Enabling Green Technology Innovation Under the TOE Framework

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**Abstract.** In the context of the global green transition, enhancing regional green technology innovation capabilities through digital empowerment has emerged as a pressing challenge. Grounded in the TOE (Technology-Organization-Environment) framework, this study integrates three dimensions—technological, organizational, and environmental—to empirically investigate the configurational pathways across 30 Chinese provinces using fuzzy-set Qualitative Comparative Analysis (fsQCA). Key findings reveal: (1) No single condition independently drives high-level green technology innovation, requiring synergistic interactions across multiple dimensions; (2) Three distinct pathways emerge—an industry-oriented with environmental synergy type, a dual-core innovation-finance type, and a multidimensional integration type; (3) Digital innovation capacity, digital industrial clustering, and digital financial ecosystems serve as universal core conditions, while other factors establish adaptive mechanisms through complementary or substitutive relationships. Theoretical contributions are threefold: (1) A configurational TOE framework integrating technological, organizational, and environmental dimensions is proposed, addressing the prior literature's overemphasis on isolated micro-level variables and linear causality; (2) Methodologically, we pioneer the application of fsQCA to decode the synergistic mechanisms of digital empowerment in GTI, overcoming the limitations of conventional regression in capturing nonlinear interactions and equifinality; (3) Contextually, we validate the TOE framework in China's regional governance context by incorporating localized indicators, offering a reference for developing countries' sustainability transitions. Practically, this study challenges the "one-size-fits-all" governance paradigm by proposing three differentiated pathways (industry-environment synergy, innovation-finance dual-core, and multidimensional integration), emphasizing adaptive policy portfolios tailored to regional digital maturity.

**Keywords:** TOE, Digitalization, Green Technology Innovation, fsQCA.

## 1. Introduction

Amidst the deepening interlinkages between global climate governance and sustainable development goals, green technology innovation (GTI) has emerged as a pivotal breakthrough to address environmental constraints and energy crises. Major economies worldwide are actively constructing strategic GTI systems: China's *Implementation Plan for Market-Oriented Green Technology Innovation System (2023-2025)* positions GTI as the core engine for high-quality development, while the EU's *2050 Long-Term Strategy* leverages green technologies to achieve carbon neutrality. Japan's *Innovative Environmental Technology Strategy* prioritizes resource efficiency and ecological preservation through technological advancement, and UNCTAD's *Technology and Innovation Report 2023* underscores GTI's critical role in developing nations' sustainability transitions. These policy alignments signify GTI's evolution from a supplementary tool to a strategic infrastructure for global sustainable development.

Enhancing GTI capabilities to accelerate sustainability has become a focal global agenda. Existing studies reveal dual-driver mechanisms of GTI from digital empowerment perspectives. In the digital technology dimension, scholars emphasize infrastructure foundations (Li et al., 2023)[1], open innovation synergies (Bo et al., 2024)[2], and application competencies (Zhang and Yao, 2023)[3]. In the digital economy dimension, research explores green credit mitigation (Hong and Li, 2021)[4], inclusive finance facilitation (Zhang et al., 2019)[5], and market maturity catalysis (Shi et al., 2024)[6].

However, current literature predominantly focuses on firm-level analyses using linear regression to examine the net effects of isolated variables, inadequately addressing the nonlinear, configurational causality among multilevel conditions at regional scales.

To transcend these limitations, this study integrates the TOE (Technology-Organization-Environment) framework following Li's (2023) approach, systematically analyzing GTI performance across 30 Chinese provinces[7]. Adopting Li's (2024) methodological proposition[8], we employ fuzzy-set Qualitative Comparative Analysis (fsQCA) to decode the complex interdependencies among digital empowerment factors. Theoretically, while existing methodologies (e.g., linear regression) focus on the net effects of single variables, our fsQCA-based configurational approach reveals equifinal pathways and conjunctural causality, providing a novel lens to decode how digital empowerment mechanisms diverge across regions. We enrich the TOE framework with China-specific contextualization by embedding indicators such as the Digital Government Development Index and Digital Financial Inclusion Index, bridging the theoretical gap in applying Western-originated frameworks to developing economies this research bridges the macro-micro divide in GTI studies, while practically informing policymakers with differentiated strategies aligned with regional digital maturity levels. Our findings challenge conventional "one-size-fits-all" governance models, advocating instead for adaptive policy portfolios that synchronize technological leapfrogging with institutional innovation.

## 2. Theoretical Foundation and Model Construction

### 2.1. Technological Dimension

Digital technology, as the foundational driver of green innovation, emphasizes its intrinsic characteristics in enabling technological applications, particularly its empowerment effects on innovation. Scholarly investigations into digital technology's impact on green technology innovation (GTI) span multiple perspectives. From the perspective of digital technology facilities, Xue (2022) demonstrates that digital infrastructure construction reduces urban carbon emissions by accelerating GTI[9]. Shi Dan demonstrated through the construction of a linear regression model that digital infrastructure is a pivotal factor in mediating the positive effects of integrating the digital and real economies on green innovation[10]. In the context of the digital economy, intra-organizational open innovation ecosystems facilitate knowledge flow, reshape value co-creation between firms and stakeholders, and mature green innovation systems (Bo et al., 2023)[2]. Cao (2023)[11] and Ma (2024)[12] identifies digital talent as a critical variable for GTI enhancement, and research also reveals that shortages in digital human capital constitute key bottlenecks for sustained GTI advancement (Han and Liu, 2024)[13].

### 2.2. Organizational Dimension

Regional GTI performance is shaped by organizational factors operating through three mechanisms: scale constraints, management structure standardization, and resource coordination efficiency. Under digital governance frameworks, governments—as regional administrators—drive informatization through large-scale digital deployment, optimizing resource allocation precision (Li et al., 2023; Li and Xiao)[7,14]. Empirical studies reveal an inverted U-shaped relationship between government subsidies and corporate GTI, with the moderating effect of market concentration between the two being either inhibitory or promotional (Kong et al.,2024; Pei et al., 2019)[15,16]. While existing research underscores governmental roles, emerging evidence suggests industrial agglomeration influences GTI through knowledge spillovers and competition effects (Liu and Zhao, 2015)[17], though outcomes vary across empirical contexts.

## 2.3. Environmental Dimension

The digital environment exhibits multi-dimensional GTI drivers. Technologically, it supports regional intelligent digital transformation through infrastructure upgrading (Li et al., 2023)[7]. Economically, digital inclusive finance alleviates financing constraints, stimulates grassroots innovation, and narrows regional GTI disparities (Sun et al., 2024; Xue and Zhang, 2022)[18,19]. At the same time, the imposition of environmental taxes and the internalization of environmental costs will force enterprises to innovate in a green way (Yu et al., 2019)[20]. Market maturity further amplifies corporate GTI engagement, as evidenced by Shi's (2024) findings on enterprise behavioral adaptation[6]. In addition, Qi (2018) proves that the existence of a market for trading environmental rights and interests also induces green technological innovation in firms by using the difference-in-difference-in-differences (DDD) method[21]. Collectively, these pathways establish heterogeneous GTI landscapes across regions.

## 2.4. Literature Review and Model Development

Existing studies exhibit two critical gaps: (1) overemphasize micro-level firm analyses, neglecting spatial synergies in regional innovation systems. (2) methodological reliance on linear regression, insufficient for capturing nonlinear interactions among concurrent conditions. GTI advancement inherently involves equifinality (multiple pathways) and conjunctural causality (interdependent conditions), rendering single-variable analyses inadequate.

Adopting Li's (2023) TOE framework[7], this study proposes a configurational model (Figure 1) integrating:

(1) Technology: Level of Digital Infrastructure (LDI), Digital Technology Capacity (DTC), Digital Talent Pool (DTP).

(2) Organization: Digital Government (DG), Digital Industry (DI).

(3) Environment: Digital Financial Ecosystems (DFE), Level of Digitization (LD), Market Maturity (MM).

This triadic framework operationalizes the synergistic interplay among 8 core variables, enabling systematic analysis of how digital empowerment configurations differentially drive GTI across China's provinces.

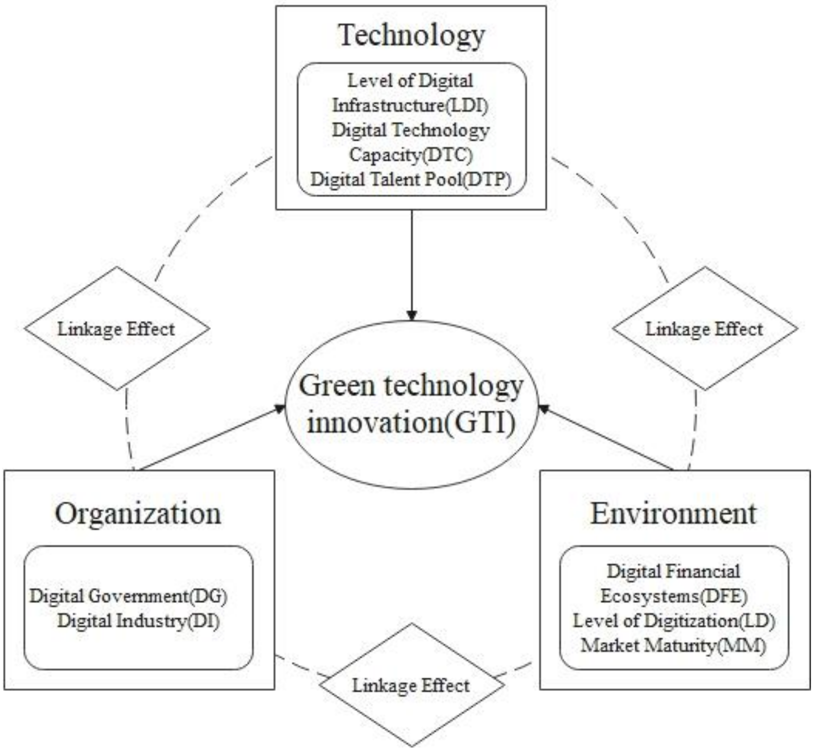

**Figure 1.** Research model

# 3. Research Design

## 3.1. Research Methodology

Qualitative Comparative Analysis (QCA), introduced by Ragin, is grounded in Boolean algebra, and set theory, specifically designed for analyzing complex causal relationships among multiple variables. It treats each case as a series of “configurations” of conditional variables, aiming to find combinations of conditional variables that lead to the appearance/non-appearance of the desired outcome, i.e. sufficient and necessary conditions, which are essentially a form of deterministic causation. The method transforms qualitative data into fuzzy sets with elements having an affiliation between 0 and 1 to reflect the degree to which the elements are related to the set. Commonalities and differences between cases are then systematically compared to reveal the combination of conditions that led to a particular phenomenon or outcome. As established earlier, the drivers of green technology innovation (GTI) exhibit multi-dimensional complexity where single factors rarely independently determine high-level outcomes. While linear regression isolates net effects of individual variables—limited to explaining singular causal relationships and symmetric associations—QCA uniquely captures interactive effects and conjunctural causation among multiple conditions (Fiss, 2011)[22]. This capability provides stronger theoretical support for identifying heterogeneous pathways to advanced GTI. Notably, fsQCA (fuzzy-set Qualitative Comparative Analysis) demonstrates methodological advantages in small or medium sample studies compared to conventional regression requiring large datasets (Li et al., 2024)[8]. Given our focus on China's 30 provincial-level units—a medium-sized sample representing regional heterogeneity—fsQCA proves particularly appropriate for it.

## 3.2. Variable Measurement and Data Sources

This study analyzes data from 30 Chinese provincial-level administrative units, excluding Tibet due to data unavailability. The outcome variable—Green Technology Innovation (GTI)—is operationalized following Kong's (2024) methodology[15], calculated as the aggregate of green invention patents and green utility model patents granted. Relevant patent data from CNRDS database. Condition variables are structured within the TOE framework.

Specifically, the Level of Digital Infrastructure (LDI) is measured using Yu's (2023) three-tier indicator system[23], computed through an integrated approach combining: (1) Entropy weight method for objective indicator weighting. (2) Linear-weighted comprehensive evaluation model for provincial scoring.

The computational formula is expressed as:

$$\left\{\begin{aligned}
&\text{Positive indicators: } y_{ij} = \frac{x_{ij} - \min\limits_{i}(x_{ij})}{\max\limits_{i}(x_{ij}) - \min\limits_{i}(x_{ij})} && (1)\\
&\text{Negative indicators: } y_{ij} = \frac{\max\limits_{i}(x_{ij}) - x_{ij}}{\max\limits_{i}(x_{ij}) - \min\limits_{i}(x_{ij})} && (2)\\
&p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}} && (3)\\
&k = \frac{1}{\ln(m)} && (4)\\
&e_j = -k\sum_{i=1}^{m} p_{ij}\ln(p_{ij})\ \left(\text{When } p_{ij} = 0\text{，specify} p_{ij}\ln(p_{ij}) = 0\right) && (5)\\
&g_j = 1 - e_j && (6)\\
&w_j = \frac{g_j}{\sum_{j=1}^{m} g_j} && (7)\\
&S = \sum_{j=1}^{n} w_j \times y_{ij} && (8)
\end{aligned}\right.$$

where $x_{ij}$ denotes the value of the $i$-th sample (province) on the $j$-th indicator ($i$ =1,2,⋯,$m$; $m$ = total samples; $j$=1,2,⋯,$n$; $n$ = total indicators). The entropy value, differentiation coefficient, and weight of the $j$-th indicator are $e_j$, $g_j$, and $w_j$ respectively. $S$ represents the comprehensive evaluation score.

We adopt the location entropy method to quantify Digital Industrial clustering (DI):

$$DM = \left(\frac{\frac{e_{iI}}{E_I}}{\frac{e_i}{E}}\right) \tag{9}$$

Where $e_{iI}$ indicates employment in information transmission and software industries in $i$. $E_I$represents national total employment in information transmission and software sectors. $e_i$ means total employment in province $i$. $E$ denotes National total employment.

Market Maturity (MM) is proxied by Fan Gang's Marketization Index. Given data availability limited to 1997-2019, we apply Ma's (2015) extrapolation algorithm[24], extending the index to 2022 using historical annual growth rates.

The remaining variables are measured in Table 1.

**Table 1.** Variable Selection and Measurement

| Conditional Variable | | Definition | Data Resource | Reference |
|---|---|---|---|---|
| Technology | Level of Digital Infrastructure (LDI) | Combined use of entropy weighting and linear weighting methods to calculate scores | China City Statistical Yearbook, China Torch Statistical Yearbook, Qichacha | Yu (2023)[23] |
| | Digital Technology Capacity (DTC) | Number of digital economy-related inventions licensed in 2022 | China National Intellectual Property Administration | Zhang (2023)[3] |
| | Digital Talent Pool (DTP) | Size of employees in the information transmission and software industry | China Software Industry Statistical Yearbook | Cao (2023)[11] |
| Organization | Digital Government (DG) | Digital Government Development Index | Center for Science & Technology Development and Governance, Tsinghua University | Wang (2021)[25] |
| | Digital Industry (DI) | Calculating the level of digital industry agglomeration using the location entropy method | China City Statistical Yearbook, China Software Industry Statistical Yearbook | Luo (2024)[26] |
| Environment | Digital Financial Ecosystems (DFE) | Digital Financial Inclusion Index | Institute of Digital Finance, Peking University, AntChain Open Labs | Zhang (2019)[5] |
| | Level of Digitization (LD) | Digital Ecology Index | National Engineering Laboratory For Big Data Analysis and Application | Qiu (2021)[27] |
| | Market Maturity (MM) | Fan Gang's Marketization Index | China Market Index Database | Shi (2024)[6] |

### 3.3. Data Calibration

In fsQCA methodology, variable calibration is essential to establish set membership relationships. This study employs the direct calibration method, anchoring the 75th, 50th, and 25th percentile values of each variable as full membership, crossover point, and full non-membership thresholds, respectively (Li et al., 2024)[8]. To resolve potential configuration attribution ambiguity caused by cases with exact 0.5 membership scores—a theoretical boundary condition in fuzzy-set logic—we implement a technical adjustment by replacing such values with 0.501. The calibration anchors for each variable are shown in Table 2.

**Table 2.** Variable Calibration

| Variable | Full Membership | Crossover Point | Full Non-Membership |
|---|---|---|---|
| GTI | 12767.750 | 6011.500 | 2753.000 |
| LDI | 1.601 | 1.511 | 0.989 |
| DTC | 42726.750 | 14200.000 | 4950.750 |
| DTP | 356120.300 | 65150.000 | 13496.000 |
| DG | 73.815 | 68.420 | 65.223 |
| DI | 0.897 | 0.632 | 0.460 |
| DFE | 397.438 | 375.390 | 355.190 |
| LD | 40.772 | 32.241 | 22.596 |
| MM | 10.479 | 9.640 | 7.921 |

# 4. Empirical Analysis

## 4.1. Analysis of Necessary Conditions

Following fsQCA analytical protocols, we first assess the necessity of individual conditions before conducting configurational analysis. Adopting Fiss's (2011) threshold criteria[22], a condition is deemed necessary if its consistency score exceeds 0.9. As shown in Table 3, high Level of Digitalization demonstrates necessity consistency (0.919) for achieving high-level Green Technology Innovation (GTI), indicating that advanced digital transformation is a prerequisite for superior GTI performance. This aligns with the theoretical premise that enhanced digitalization amplifies empowerment effects, thereby catalyzing GTI advancement. Conversely, non-high Digital Technology Capability (consistency=0.912) and non-high Digital Talent Pool (consistency=0.905) emerge as necessary conditions for non-high GTI. These necessary conditions exhibit asymmetric causality—while high digitalization enables GTI excellence, the absence of innovation capacity or talent systematically predicts GTI underperformance.

**Table 3.** Analysis of Necessary Conditions

| Conditional Variable | GTI | | ~GTI | |
|---|---|---|---|---|
| | Consistency | Coverage | Consistency | Coverage |
| LDI | 0.685 | 0.674 | 0.407 | 0.421 |
| ~LDI | 0.412 | 0.398 | 0.685 | 0.695 |
| DTC | 0.865 | 0.904 | 0.216 | 0.237 |
| ~ DTC | 0.269 | 0.246 | 0.912 | 0.877 |
| DTP | 0.885 | 0.899 | 0.250 | 0.267 |
| ~ DTP | 0.279 | 0.262 | 0.905 | 0.892 |
| DG | 0.837 | 0.752 | 0.378 | 0.357 |
| ~ DG | 0.284 | 0.303 | 0.737 | 0.826 |
| DI | 0.779 | 0.785 | 0.302 | 0.320 |
| ~ DI | 0.325 | 0.307 | 0.797 | 0.791 |
| DFE | 0.839 | 0.832 | 0.293 | 0.306 |
| ~ DFE | 0.301 | 0.288 | 0.839 | 0.845 |
| LD | 0.919 | 0.887 | 0.260 | 0.263 |
| ~ LD | 0.237 | 0.233 | 0.889 | 0.920 |
| MM | 0.882 | 0.837 | 0.286 | 0.285 |
| ~ MM | 0.247 | 0.248 | 0.837 | 0.881 |

Note: ~indicates logical not

## 4.2. Configurational Analysis

Unlike single necessary condition analysis, configurational analysis identifies combinations of sufficient conditions leading to the same outcome. Following Liu's (2024) protocol[28], we set thresholds for raw consistency, PRI consistency, and case frequency at 0.80, 0.75, and 1, respectively. Given limited prior theoretical guidance, all conditions were allowed to present or absent during truth table analysis. Core conditions were determined by comparing nested relationships between intermediate and parsimonious solutions: conditions appearing in both solutions are classified as core, while those only present in intermediate solutions are peripheral (Li et al., 2024)[8]. Detailed results are presented in Table 4.

**Table 4.** Configuration Analysis of High Green Technology Innovation

| Conditional Configuration | GTI | | | | | |
|---|---|---|---|---|---|---|
| | S1a | S1b | S1c | S2a | S2b | S3 |
| LDI | ⊗ | ⊗ | • | • | • | ⊗ |
| DTC | • | | ⊗ | ● | ● | ● |
| DTP | • | • | ⊗ | • | • | ⊗ |
| DG | • | • | ⊗ | • | ⊗ | ⊗ |
| DI | ● | ● | ● | | • | ● |
| DFE | | • | ⊗ | ● | ● | ● |
| LD | ● | ● | ● | • | ⊗ | ● |
| MM | • | • | ⊗ | • | • | ⊗ |
| Original coverage | 0.219 | 0.208 | 0.070 | 0.508 | 0.086 | 0.077 |
| Unique Coverage | 0.032 | 0.031 | 0.023 | 0.377 | 0.013 | 0.017 |
| Consistency | 1.000 | 0.994 | 0.972 | 1.000 | 1.000 | 1.000 |
| Overall solution coverage | 0.718 | | | | | |
| Consistency of the overall solution | 0.995 | | | | | |

Note: ● or • represents conditions present, ⊗ or ⊗ represents conditions absent, ● or ⊗ represents core conditions, • or ⊗ represents marginal conditions, and blanks represent conditions that may or may not be present, as in the following tables.

Since S1a, S1b and S1c have the same core conditions, and S2a and S2b have the same core conditions, with reference to Murthy (2021)[29], paths with the same core conditions are considered as equivalent paths in this paper for merger analysis. Three distinct pathways emerge for achieving high green technology innovation. The overall consistency of the solution is 0.995, indicating that 99.5% of all cases satisfying the configurations in Table 4 show high levels of green technology innovation in the region; the overall coverage of the solution is 0.718, indicating that these paths can explain 71.8% of the cases with high levels of green technology innovation. The configurational analysis reveals differentiated synergistic interactions among technological, organizational, and environmental dimensions in driving regional GTI advancement.

**(1) Industry Agglomeration-Environment Synergy-Driven Pathway**

Configurations S1a, S1b, and S1c are characterized by Digital Industry and Level of Digitization as core conditions, supplemented by auxiliary factors including Digital Technology Capacity, Digital Talent Pool, Digital Government, and Market Maturity. This configuration mechanism suggests that industrial agglomeration generates synergistic cluster effects, while advanced digital infrastructure provides foundational support for high-quality industrial development, collectively driving regional green technology innovation. Representative provinces such as Sichuan, Tianjin, Anhui, Hubei, and Henan exemplify this pathway. Taking Sichuan as a case study, designated as a National Digital Economy Innovation and Development Pilot Zone, the province ranks among China's top eight regions with digital industry revenues exceeding one trillion yuan (2024), positioning its digital economy scale at the national forefront. Strategic initiatives include establishing 23 provincial-level emerging industrial clusters, particularly accelerating deployments in frontier fields like next-generation displays and artificial intelligence. Anchored by industry leaders such as BOE and Changhong, Sichuan has cultivated a thriving semiconductor and smart display industrial ecosystem, whereby its digital agglomeration model has demonstrated remarkable success alongside sustained growth in digitalization metrics.

**(2) Innovation-Finance Dual-Core-Driven Pathway**

Configurations S2a and S2b are anchored by Digital Technology Capacity and Digital Financial Ecosystems as dual core conditions, synergistically supported by auxiliary factors encompassing the

Level of Digital Infrastructure, Digital Talent Pool, and Market Maturity. This framework highlights robust technological innovation capabilities within regional enterprises to catalyze knowledge spillovers, fostering systemic development across sectors. However, the inherently capital-intensive and high-risk nature of technological innovation imposes significant financing constraints, which are effectively mitigated by inclusive financial mechanisms enabling accessible funding channels for enterprises and individuals, thereby accelerating green technology innovation advancement. Exemplar regions include Beijing, Guangdong, Jiangsu, Zhejiang, Fujian, Shandong, Shanghai, and Shaanxi. Guangdong Province, a prime case, leads the nation in digital economy enterprises and invention patents, accounting for nearly 30% of China's total digital economy invention patents in 2022. Leveraging Shenzhen's status as a fintech hub, anchor enterprises like Huawei and Tencent drive continuous innovation spillovers, while policy-backed instruments such as green credit and Yueke Rong (Guangdong Science and Technology Finance Platform) provide strategic financial support. Shenzhen's "technology-finance dual-core" model has established a virtuous cycle where R&D breakthroughs and financial empowerment mutually reinforce.

### (3) Multidimensional Composite-Driven Pathway

Configuration S3 exemplifies a quad-core synergistic mechanism integrating Digital Technology Capacity, Digital Industry, Digital Financial Ecosystems, and Level of Digitization through multidimensional coordination across technology, organization, and environment. Henan Province, a representative case, demonstrates how systemic integration of moderate individual factors can achieve high-level green technology innovation via multi-pronged strategies. Recent initiatives include establishing blockchain-based energy management pilots and quantum information technology innovation centers, which elevated Henan’s technological innovation index. Besides, the province has prioritized technology-driven green finance, launching a variety of innovative financial products in recent years, while promoting inclusive financial mechanisms. Concurrently, its "dual-track" digital strategy—advancing computing clusters while digitizing traditional manufacturing—has led to an increasing number of core industrial projects in the digital economy and an increasing level of digitization, reflecting the strategic value of the systematic integration of multidimensional elements for innovation breakthroughs in late-developing regions.

## 4.3. Robustness Tests

To validate the robustness of configurational findings, this study employs two strategies following Zhang's (2019) methodology[30]:

(1) Threshold adjustment: Raising the consistency threshold from 0.8 to 0.9 yields identical pathway configurations. The results of the configuration are in complete agreement with the previous results (Table 4) and are therefore not shown again.

(2) Measurement substitution: Replacing green patent applications with granted green patents as the outcome variable produces equivalent solutions, with slightly improved coverage and consistency (Table 5).

**Table 5.** Robustness Tests

| Conditional Configuration | GTI | | | | | |
|---|---|---|---|---|---|---|
| | S1a | S1b | S1c | S2a | S2b | S3 |
| LDI | ⊗ | ⊗ | • | • | • | ⊗ |
| DTC | • | | ⊗ | ● | ● | ● |
| DTP | • | • | ⊗ | • | • | ⊗ |
| DG | • | • | ⊗ | • | ⊗ | ⊗ |
| DI | ● | ● | ● | | • | ● |
| DFE | | • | ⊗ | ● | ● | ● |
| LD | ● | ● | ● | • | ⊗ | ● |
| MM | • | • | ⊗ | • | • | ⊗ |
| Original coverage | 0.222 | 0.211 | 0.071 | 0.513 | 0.087 | 0.078 |
| Unique Coverage | 0.032 | 0.032 | 0.023 | 0.381 | 0.013 | 0.017 |
| Consistency | 1.000 | 0.997 | 0.972 | 1.000 | 1.000 | 1.000 |
| Overall solution coverage | 0.726 | | | | | |
| Consistency of the overall solution | 0.996 | | | | | |

These sensitivity analyses confirm the reliability of our findings in explaining how digital empowerment enables high-level green technology innovation.

## 5. Research Conclusions and Prospects

### 5.1. Research Conclusions

From a configurational perspective, this study integrates the TOE framework with fuzzy-set Qualitative Comparative Analysis (fsQCA) to systematically decode the synergistic mechanisms among technology, organization, and environment across 30 Chinese provinces, revealing heterogeneous pathways for digital empowerment enabling regional green technology innovation (GTI). Key findings include:

(1) Concurrent multiplicity: High-level GTI requires nonlinear synergy across multidimensional conditions rather than isolated drivers from single dimensions.

(2) Analysis of Necessary Conditions: High levels of digitization are necessary for high levels of green technology innovation, while non-high levels of digital technological innovation capacity and non-high levels of digital talent pool are necessary for non-high levels of green technology innovation.

(3) Equifinal pathways: Three distinct yet equally effective configurations emerge—Industry Agglomeration-Environment Synergy-Driven Pathway, Innovation-Finance Dual-Core-Driven Pathway, and Multidimensional Composite-Driven Pathway

(4) Core-periphery dynamics: Digital Innovation Capacity, Digital Industrial, and Digital Financial Ecosystems consistently serve as universal core conditions, while peripheral factors form dynamic adaptive mechanisms through complementary or substitutive relationships.

### 5.2. Theoretical Contributions

Based on the existing research results, this paper takes the TOE framework as the core and utilizes the fsQCA methodology to study the realization path of digitally-enabled high-level green technological innovation in China at the current stage, and makes contributions in the following aspects:

(1) An indicator system covering the three dimensions of technology, organization, and environment is constructed under the TOE framework, which makes up for the shortcomings of

existing studies in the insufficient integration of conditional variables at the regional level, and provides a new paradigm for the study of green technological innovation.

(2) Combined with Chinese characteristic indicators (e.g., Digital Financial Inclusion Index, Digital Government Development Index, Fan Gang's Marketization Index, etc.), the applicability of the TOE framework in China's regional green technological innovation research is verified to provide theoretical support for the research on digital transformation in developing countries.

(3) Combining the TOE framework with fsQCA to systematically analyze the multidimensional synergistic mechanism of digitally-enabled green technological innovation breaks through the dependence of traditional linear regression methods on a single causality, and reveals the complex causality of multiple concurrency and different paths to the same destination.

### 5.3. Practical Implications

Based on empirical research in 30 provinces in China, this paper systematically reveals the differentiated realization paths of digitization-enabled green technological innovation, and provides the following practical insights for promoting high-quality development:

(1) Focus on the construction of digital technological innovation capacity, build a digital transformation mode led by technological breakthroughs, and strengthen the ability of core technology research.

(2) Accelerating the layout of digital industry clusters, relying on the national arithmetic hub nodes and strategic emerging industry clusters, pulling industry chain synergistic innovation through leading enterprises, and fully releasing the scale effect and technology spillover effect of industrial agglomeration.

(3) Aiming at the high-input characteristics of innovation activities, it is suggested that managers should improve the green financial policy toolbox, develop digital credit products to meet the needs of small and medium-sized enterprises (SMEs) and build a multi-level capital market to alleviate the financing constraints.

This paper provides policymakers with a practical framework of “multi-dimensional synergy and precise policy implementation”, emphasizing the need to choose appropriate paths based on regional resource endowments. Based on the study of China, we can extend the findings to other developing countries. Developing countries should choose the appropriate path based on resource endowment, promote the deep integration of digitalization and greening, and ultimately achieve a two-way leap in technological innovation and eco-efficiency.

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