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# A Configurational Pathway Analysis of Digital Economy and Green Technology Innovation

**Jing Jiang**

School of Economics and Management, Wenzhou University of Technology, Zhejiang, China
Email: christinejiang2@hotmail.com

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## Abstract

Green technological innovation is essential for promoting high-quality regional economic growth. The digital economy, characterized by penetration, integration, and sustainability, significantly enhances the efficiency of green innovation. However, existing research has largely focused on singular aspects of green development, overlooking comprehensive configurational analyses and the varied development pathways of cities. This gap hinders the identification of optimal and suboptimal strategies. To examine the configurational effects and driving mechanisms of urban digital economy development within the context of green technological innovation, 25 cities in the Jiangsu-Zhejiang-Shanghai region were selected as the research sample. Four key dimensions were analyzed: digital infrastructure, digital information development, digital innovation, and digital inclusive finance. The fuzzy-set qualitative comparative analysis (fsQCA) method was employed, and multiple high-efficiency configurational pathways among these cities were identified. Significant variation in the core and auxiliary conditions of these pathways was observed, underscoring the importance of multidimensional synergies in the digital economy as a driving force for enhancing the efficiency of green technological innovation. It was found that the relationship between digital economy development and green technological innovation is complex, with no single factor driving the prosperity of green innovation. Two high-efficiency pathways for green technological innovation were identified: the "information infrastructure-financial inclusion" pathway and the multi-factor integrated driving models of "information-innovation-inclusion". Constructive recommendations were provided for cities with high-efficiency and low-efficiency pathways to enhance green innovation outcomes.

## Keywords

Green Technology Innovation, Digital Economy, Configurational Effects, fsQCA, Urban Areas

## 1. Introduction

The integration of the digital economy and green technological innovation has become a crucial driver for sustainable development during the global economic transition. In the economically dynamic Jiangsu-Zhejiang-Shanghai region, the digital economy not only stimulates local economic growth but also fosters new paradigms of development through advancements in green technology. Technological progress in the digital economy enhances sustainability and economic performance (Ding et al., 2021; Faisal et al., 2022) and accelerates high-quality growth, a trend particularly evident in this region (Zhao et al., 2022). The Jiangsu-Zhejiang-Shanghai region is one of the most economically dynamic and technologically advanced areas in China, serving as a national hub for digital economy development and green innovation. This region's unique combination of robust digital infrastructure, high levels of investment in technological innovation, and supportive policy environment makes it an ideal focus for exploring the synergies between the digital economy and green technological innovation. Furthermore, the region's rapid urbanization and industrialization have intensified environmental challenges, creating an urgent need to identify effective pathways for sustainable development. Green technological innovation contributes to sustainable development by reducing resource consumption, mitigating environmental pollution, and encouraging innovative investments (Pang et al., 2021; Vargas-Hernández et al., 2023). As an emerging economic model, the digital economy supports the application and diffusion of green technologies by optimizing resource use and improving production efficiency (Hao et al., 2022). Furthermore, its role in upgrading industrial structures promotes the transition of traditional industries toward greener and smarter models (Li, 2021; Zhao et al., 2022).

Existing research identifies the digital economy as a key driver of regional transformation and upgrading, with notable spillover effects. However, the configurational aspects of urban digital economy development in the context of green technological innovation remain underexplored. A systematic framework for identifying digital pathways that enhance the efficiency of green technology innovation has yet to be established. This research gap hinders the identification of optimal pathways and the improvement of suboptimal ones, limiting further advancement of high-quality development in the Jiangsu-Zhejiang-Shanghai region. Therefore, this study focuses on examining the configurational effects of the digital economy on green technological innovation, positioning the digital economy as the antecedent variable.

## 2. Literature Review

The rapid development of the digital economy has created new opportunities for transforming and upgrading traditional industries, while also introducing challenges in managing and controlling carbon emissions, particularly in enhancing the efficiency of green technological innovation.

### 2.1. Green Technology Innovation under Carbon Emission Targets

Achieving carbon emission targets has brought the efficiency of green technological innovation to the forefront for governments and enterprises worldwide. Green technological innovation serves as a vital tool for addressing climate change and promoting sustainable economic growth. While reducing energy intensity can lower local carbon emissions, spillover effects may unintentionally increase emissions in neighboring regions, highlighting the need for green technological innovation to enhance the effectiveness of carbon reduction strategies (Pang, Ding, & Shen, 2023). Government policies and financial support are pivotal in advancing green technological innovation. In China, environmental regulations and R&D funding have significantly influenced its trajectory (Guo, Xia, Sheng, & Zhang, 2018). Green innovation strategies not only improve corporate performance but also mitigate supply chain risks related to environmental sustainability (Wang & Liu, 2022). The spatial dynamics of green technological innovation also affect its efficiency. Regional disparities in technological progress can undermine efforts to reduce carbon emissions, underscoring the importance of balanced industrial development (Yuan, Zhang, Wang, Ma, & Niu, 2024). Furthermore, green technological innovation is closely tied to corporate governance. Stakeholder pressure for transparency in carbon emissions drives companies to adopt sustainable practices, thereby strengthening their innovation capabilities (Kılıç & Kuzey, 2019). The efficiency of green technological innovation, under carbon emission targets, is shaped by the interaction of regulatory frameworks, regional dynamics, and corporate governance.

### 2.2. Relationship Between the Digital Economy and Green Technology

In the context of global efforts toward sustainable development and carbon neutrality, the intersection of the digital economy and green technology has become a key area of focus. The digital economy has been found to positively influence green technological innovation within enterprises. Technological advancements driven by the digital economy not only enhance digital technologies but also facilitate their integration with energy systems, promoting low-carbon development in resource-intensive industries (Kılıç & Kuzey, 2019). By optimizing resource allocation and improving energy efficiency, the digital economy plays a crucial role in supporting sustainable growth. The integration of digital technologies with traditional industries has significantly improved energy efficiency and innovation capabilities (Zeng et al., 2023). In addition, the digital economy has contributed to reducing carbon emissions (Cui et al., 2023), reinforcing its role as a catalyst for achieving climate neutrality (Haller et al., 2023). These findings underscore the transformative potential of the digital economy in advancing green technological innovation and facilitating the global transition toward sustainable, low-carbon development pathways.

### 2.3. Theoretical Connection between the Digital Economy and Green Technological Innovation

The digital economy, defined by the integration of digital technologies into economic activities, has been shown to enhance the efficiency of green technological innovation through various mechanisms. Advanced digital technologies, such as 5G, have significantly improved the efficiency and quality of green innovation activities (Fan & Li, 2024). Green technological innovation not only supports environmental protection objectives but also enhances economic efficiency (Yi et al., 2022). The digital economy plays a vital role in fostering urban green innovation (Fu, 2024), although its influence on green technological innovation varies significantly across regions (Li et al., 2022). By facilitating information sharing, promoting collaboration, and introducing advanced technologies, the digital economy collectively enhances the efficiency of green innovation.

## 3. Methodology

The fsQCA method, which combines set theory and Boolean algebra, was employed to examine the relationship between antecedent conditions (and their combinations) and outcomes, revealing the underlying complex causal mechanisms. Although fsQCA is typically applied to cross-sectional data, this study adapted the method to analyze temporal data (2016-2023) by incorporating panel data processing techniques. The panel data were first prepared by ensuring that the condition variables preceded the outcome variable through time-lagged design. Data from multiple time points were collected and calibrated using consistent standards across all years, employing software tools such as fsQCA3.0. Missing data were handled to ensure completeness, and a truth table was constructed to include all combinations of conditions, calculating the frequency and consistency of the outcome variable for each configuration. By analyzing the truth table, key condition combinations were identified, and their logical consistency and coverage were verified. This approach enhances fsQCA's capacity to infer causality and ensures the reliability of results by addressing temporal changes in the data. Compared to methods like SEM or panel regression, fsQCA provides unique advantages in uncovering causal complexity and asymmetrical relationships. While SEM and panel regression excel at testing linear and temporal dynamics, fsQCA focuses on identifying configurational pathways that account for multiple equivalent solutions, making it particularly suitable for analyzing synergies in the digital economy and green technological innovation. By adopting these panel data handling techniques, this study ensures that fsQCA can effectively capture the dynamic relationships between condition variables and the outcome variable over time, aligning with the study's aim to explore high- and low-efficiency pathways. This method is characterized by relational asymmetry, multiple equivalence, and causal complexity. Unlike traditional regression analysis, which can test interaction effects by introducing interaction terms, regression models often face challenges in interpreting results when multicollinearity is present. In contrast, fsQCA allows for a systematic analysis of interactions among multiple antecedent variables and their combinations, effectively identifying the dominant pathways leading to specific outcomes. For this study, fsQCA was applied to explore how different dimensions of the digital economy in Chinese cities influence green technological innovation. The analysis process included calibrating variables, performing necessity analysis for individual conditions, conducting sufficiency analysis, and performing robustness tests.

## 3.1. Variable Setting

### 3.1.1. Condition Variables

The development of the digital economy has shown non-linear impacts on carbon emissions, along with notable spatial spillover effects. Based on the "Statistical Classification of the Digital Economy and Its Core Industries (2021)" and relevant academic studies, combined with the specific development status of the digital economy in Chinese cities, this study constructed a digital economy development index encompassing four dimensions: digital infrastructure, digital information development, digital innovation development, and digital inclusive finance (see Table 1). Digital infrastructure refers to fixed and mobile network infrastructure. Digital information development reflects the foundation of informatization and the influence of digital information. Digital innovation focuses on the foundation and role of innovation activities in the digital domain. The entropy method was applied to assess the overall level of digital economy development.

**Table 1.** Digital economy development level indicators.

| Primary Indicator | Secondary Indicator | Tertiary Indicator | Definition |
|---|---|---|---|
| Digital Economy Development Level (DED) | Digital Infrastructure | Fixed Network Infrastructure | Internet access port density, mobile phone penetration rate |
| | | Mobile Network Infrastructure | Number of broadband internet users per 10,000 people, number of mobile phone users per 10,000 people |
| | Digital Information | Information Foundation | Optical cable density, mobile telephone exchange density, proportion of information technology practitioners, proportion of enterprises engaged in e-commerce transactions |
| | | Information Influence | Telecommunication business volume per 10,000 people, software business revenue per 10,000 people, e-commerce sales |
| | Digital Innovation | Digital Innovation Foundation | R&D expenditure as a proportion of GDP |
| | | Digital Innovation Influence | Number of digital patent applications granted per 10,000 people |
| | Digital Inclusive Finance | Level of Digital Inclusive Finance | Breadth of digital financial coverage, depth of digital financial usage, degree of digitalization of inclusive finance |

Source: author.

#### 3.1.2. Outcome Variables

Drawing on previous research findings, this study emphasized the framework, indicators, and influencing factors of green technological innovation (Wang, Li, & Wang, 2023). Following the input-output principle, an evaluation system for green technological innovation was developed, incorporating both input and output dimensions for comprehensive measurement (see Table 2).

Table 2. Green technological innovation indicator system.

| Type | Element | Secondary Indicators |
|---|---|---|
| Input | Human Resource Input | Number of research personnel<br>Number of students in higher education institutions |
| | Financial Input | Research funding expenditure |
| | Energy Input | Energy consumption |
| Output | Desired Output | Local Gross Domestic Product (GDP)<br>Number of patents granted<br>Average urban resident income |
| | Undesired Output | Carbon emissions |

Source: author.

**Human Resource Input:** The number of research personnel and students enrolled in higher education institutions served as measurement indicators, reflecting the core human resource foundation for green innovation activities (Wong, 2012).

**Financial Input:** Research funding expenditure was used as a representative indicator, illustrating the financial guarantees and institutional environment essential for green innovation activities. This approach draws on measurement methods from existing studies (Guo et al., 2018).

**Energy Input:** Energy consumption was measured to represent the essential resource input required for green technological innovation. The data were calculated using a "bottom-up" approach (Peng et al., 2022).

**Positive Outputs:** Positive outputs include economic, technological, and social benefits. Economic benefits were measured by total revenue, technological benefits by the number of patents granted, and social benefits through indicators such as average wages (Liu & Yang, 2023). These metrics reflect the positive impact of green technological innovation in reducing income disparities and advancing common prosperity (Wong, 2012).

**Negative Outputs:** Negative outputs primarily focus on environmental burdens, including carbon emissions. Data were aggregated using a "bottom-up" approach to assess the potential environmental impacts of green technological innovation activities (Urbaniec et al., 2021).

Based on the constructed indicator system, the Sup-SBM model was applied to calculate the efficiency of green technological innovation. This model integrates input and output factors, providing a comprehensive evaluation of the efficiency of green technological innovation. In the Sup-SBM model, "high-efficiency" and "low-efficiency" are operationally defined based on efficiency scores for green technological innovation. Cities at the 95th percentile or above are classified as fully efficient (full membership), demonstrating optimized resource allocation and excelling in maximizing positive outputs (e.g., patents and economic benefits) while minimizing undesired outputs (e.g., carbon emissions), thus serving as benchmarks for green innovation. Cities at the 50th percentile (crossover point) represent a transitional state; although they may have advantages in areas such as financial input or human resources, they face challenges in achieving synergy and balance between inputs and outputs. This distinction highlights best practices in high-efficiency cities while identifying key areas for improvement in less efficient cities, providing a foundation for deeper analysis of green innovation efficiency.

### 3.2. Data Sources

The Jiangsu-Zhejiang-Shanghai region comprises a total of 25 cities, which were selected as the research sample based on their economic and technological diversity. Conducting the study at the city level enhances the granularity of the analysis, enabling a deeper understanding of how local policies, infrastructure, and innovation systems influence green innovation outcomes. This regional focus not only addresses shared challenges but also captures the unique dynamics of individual cities, ensuring the research is comprehensive and targeted. This study analyzed data from 2016 to 2023, considering data availability during this period. Input-output data related to digital economy development indicators and green technological innovation were primarily sourced from the *China Urban Statistical Yearbook*, local *Statistical Yearbooks*, and the *National Economic and Social Development Statistical Bulletin*. Data for the Digital Inclusive Finance Index were obtained from the Digital Finance Research Center of Peking University. Energy consumption and carbon emissions data were calculated, while additional data were retrieved from the listed companies database on the China National Knowledge Infrastructure (CNKI) Research Data Service Platform (CNRDS). To account for price changes, monetary indicators such as regional GDP and average urban resident income were adjusted for inflation, using 2015 as the base year. Missing data were supplemented using linear interpolation.

### 3.3. Calibration

Following relevant studies on fsQCA (Gao & Liu, 2022), variable calibration was categorized into three levels: the 95th percentile for full membership, the 50th percentile as the crossover point, and the 5th percentile for full non-membership. Outcome and antecedent variables were transformed into fuzzy sets with values ranging from 0 to 1, allowing for more precise normalization of the fuzzy sets (see **Table 3**).

**Table 3.** Calibration of variables.

| Variables | Indicators | Full membership | Cross-over point | Full non-membership |
|---|---|---|---|---|
| Outcome Variable | Green Technological Innovation Indicator | 0.98 | 0.053 | 0 |
| Condition Variables | X1 Fixed Network Infrastructure | 0 | 0.79 | 0 |
| | X2 Mobile Network Infrastructure | 0.434 | 0.3338 | 0.2715 |
| | X3 Information Foundation | 0.3857 | 0.3012 | 0.2522 |
| | X4 Information Influence | 0.3632 | 0.2307 | 0.1653 |
| | X5 Digital Innovation Foundation | 0.4142 | 0.3472 | 0.3133 |
| | X6 Digital Innovation Influence | 0.3804 | 0.2917 | 0.2378 |
| | X7 Level of Digital Inclusive Finance | 0.6529 | 0.6012 | 0.5814 |

Source: author.

# 4. Results Analysis

## 4.1. Necessity Analysis

Consistency is a key indicator used to determine whether a single condition variable serves as a sufficient or necessary condition for the outcome variable. Typically, the consistency threshold is set at 0.9. A condition with a consistency value exceeding 0.9 is regarded as necessary, while a value below this threshold indicates that the condition is not necessary. As shown in Table 4, the consistency values of all antecedent variables were below 0.9, suggesting that no single dimension of the digital economy is sufficient to independently improve the efficiency of green technological innovation. However, these conditions still hold explanatory power for the observed outcomes. Therefore, further exploration is required to examine the configurational effects of antecedent variables on enhancing green technological innovation efficiency from the perspective of the digital economy. Such analysis aims to uncover the complex causal relationships among various dimensions of the digital economy in driving the green innovation process.

**Table 4.** Analysis of necessary conditions.

| Condition | | High Green Technological Innovation | | Low Green Technological Innovation | |
|---|---|---|---|---|---|
| | | Consistency | Coverage | Consistency | Coverage |
| X1 | High Fixed Network Infrastructure | 0.745 | 0.610 | 0.664 | 0.740 |
| ~X1 | Low Fixed Network Infrastructure | 0.775 | 0.740 | 0.635 | 0.770 |
| X2 | High Mobile Network Infrastructure | 0.789 | 0.820 | 0.714 | 0.702 |
| ~X2 | Low Mobile Network Infrastructure | 0.721 | 0.734 | 0.820 | 0.765 |
| X3 | High Information Foundation | 0.745 | 0.898 | 0.437 | 0.475 |
| ~X3 | Low Information Foundation | 0.713 | 0.705 | 0.892 | 0.775 |
| X4 | High Information Influence | 0.621 | 0.701 | 0.772 | 0.790 |
| ~X4 | Low Information Influence | 0.643 | 0.607 | 0.716 | 0.645 |
| X5 | High Digital Innovation Foundation | 0.609 | 0.701 | 0.624 | 0.670 |

**Continued**

| | | | | | |
|---|---|---|---|---|---|
| ~X5 | Low Digital Innovation Foundation | 0.710 | 0.675 | 0.723 | 0.638 |
| X6 | Hig Digital Innovation Influence | 0.630 | 0.688 | 0.646 | 0.652 |
| ~X6 | Low Digital Innovation Influence | 0.681 | 0.681 | 0.686 | 0.641 |
| X7 | Hig Level of Digital Inclusive Finance | 0.894 | 0.895 | 0.416 | 0.455 |
| ~X7 | Low Level of Digital Inclusive Finance | 0.556 | 0.495 | 0.894 | 0.761 |

Source: author. *Note*: ~ indicates the absence of a condition.

### 4.2. Sufficiency Analysis

In this study, based on the seven selected condition variables, the constructed truth table revealed $2^7$ configurational paths (a total of 128 pathways). Given the medium to small sample size and the distribution of cases in the truth table, the frequency threshold was set to 1, and the raw consistency threshold was set to 0.8. Based on these criteria, the results of the configurational analysis are presented in Table 5.

**Table 5.** Configurational analysis results for green technological innovation.

| **Conditions** | | High Green Technological Innovation | | | Low Green Technological Innovation | | |
|---|---|---|---|---|---|---|---|
| | | H1 | H2 | H3 | L1 | L2 | L3 |
| Digital Infrastructure | Fixed Network Infrastructure | ⊗ | • | • | ⊗ | • | • |
| | Mobile Network Infrastructure | ⊗ | ⊗ | • | • | • | |
| Digital Information | Information Foundation | ● | ● | ● | ⨂ | ⨂ | ⨂ |
| | Information Influence | • | ⊗ | • | ⨂ | ⊗ | ● |
| Digital Innovation | Digital Innovation Foundation | • | ● | ● | ⨂ | ⨂ | ⨂ |
| | Digital Innovation Influence | ⊗ | • | ⊗ | • | ● | |
| Digital Inclusive Finance | Level of Digital Inclusive Finance | ● | ● | ● | ⊗ | ⊗ | ⨂ |
| Consistency | | 0.928 | 0.915 | 0.925 | 0.880 | 0.839 | 0.865 |
| Raw coverage | | 0.298 | 0.288 | 0.269 | 0.381 | 0.280 | 0.191 |
| Unique coverage | | 0.024 | 0.049 | 0.127 | 0.096 | 0.224 | 0.049 |
| Solution coverage | | 0.572 | | | 0.512 | | |
| Solution consistency | | 0.912 | | | 0.875 | | |

Source: author. *Note*: ● Core condition is present, ⨂ Core condition is absent, • Auxiliary condition is present, ⊗ Auxiliary condition is absent. A blank space indicates that the condition may be either present or absent.

Three high-efficiency configurational paths demonstrated substantial explanatory power, with a combined coverage of 0.572 and an overall consistency of 0.912. These results highlight the significant role these paths play in explaining how the digital economy contributes to the enhancement of green technological innovation efficiency. Path H1 exhibited a consistency of 0.928 and a coverage of 0.298, explaining approximately 30% of the cases. The key factors in this path were information infrastructure and the digital inclusive finance index, with information influence and the foundation of digital innovation as supporting conditions. Hangzhou serves as a typical example of this path. Path H2, with a consistency of 0.915 and a coverage of 0.288, also explained around 30% of the cases, with Shanghai as a prominent representative. Path H3, with a consistency of 0.925 and a coverage of 0.269, accounted for 27% of the cases, with Suzhou as a typical instance. The core elements of both Path H2 and H3 included information infrastructure, the foundation of digital innovation, and the level of digital inclusive finance. However, Path H2 featured fixed network infrastructure and the influence of digital innovation as auxiliary conditions, while Path H3 incorporated both fixed and mobile network infrastructures, along with the influence of informatization as supporting factors. In summary, the core elements driving the high-efficiency configurational strategies in these three paths were information infrastructure and the level of digital inclusive finance. These factors are crucial in enhancing green technological innovation efficiency, while fixed and mobile network infrastructures, as well as the influence of informatization, also play important roles.

The three low-efficiency configurational paths provide insights into the limitations of the digital economy in enhancing green technological innovation efficiency. With an overall consistency of 0.875 and a total coverage of 0.512, these paths explain more than half of the sample cases. Across these configurations, inadequate information infrastructure, the influence of digital information, and a weak foundation of digital innovation emerge as primary barriers to improving green technological innovation efficiency. Quzhou serves as a typical example of a city facing these constraints. Among these paths, Path L2 shows a consistency of 0.839 and a coverage of 0.280. The main limiting factors in this path are insufficient information infrastructure and a weak digital innovation foundation, with Zhenjiang representing this configuration. Path L3, with a consistency of 0.865 and a coverage of 0.191, is characterized by limitations such as inadequate information infrastructure, a lack of digital innovation foundation, and low levels of digital inclusive finance. Huai'an and Lianyungang exemplify cities following this path. These findings do not suggest that cities associated with low-efficiency configurations are universally underperforming in terms of digital economy development or green technological innovation efficiency. Instead, they indicate that the promotion of green technological innovation efficiency by the digital economy is constrained by specific barriers or developmental bottlenecks. A comparison of these three paths reveals that the primary causes of low-efficiency configurations are inadequate information infrastructure and a weak digital innovation foundation, with insufficient levels of digital inclusive finance also playing a significant role.

The core conditions of the high-efficiency paths were fully satisfied, while the synergistic effects of auxiliary conditions further enhanced efficiency. In contrast, the core conditions of the low-efficiency paths were either insufficient or absent, directly constraining the potential for improving green technological innovation efficiency. Representative cities following high-efficiency paths, such as Hangzhou, Shanghai, and Suzhou, demonstrated well-coordinated development of the digital economy's core and auxiliary conditions, significantly driving efficiency improvements. Conversely, typical cities on the low-efficiency paths, such as Quzhou, Zhenjiang, and Huai'an, faced notable deficiencies in information infrastructure, digital innovation foundations, and inclusive financial services, which emerged as major barriers to enhancing efficiency. The high-efficiency paths underscore the importance of information infrastructure, digital innovation capability, and inclusive finance in driving green technological innovation. These paths provide valuable lessons through the practices of exemplary cities. On the other hand, the low-efficiency paths highlight developmental bottlenecks, offering clear directions for improvement. The selection of representative cities was based on their alignment with the high-efficiency and low-efficiency pathways identified in the configurational analysis. These cities were determined by examining their empirical data, consistency values, and coverage within each pathway. These paths provide valuable lessons through the practices of exemplary cities. On the other hand, the low-efficiency paths highlight developmental bottlenecks, offering clear directions for improvement. Strengthening information infrastructure, enhancing digital innovation capabilities, and expanding the coverage of inclusive financial services are identified as priority areas for cities on the low-efficiency paths. This comparison of pathways offers targeted strategic guidance for promoting green technological innovation across cities with varying levels of development.

### 4.3. Analysis of High Green Technological Innovation

Two primary driving models of digital development were identified: the dual-factor interactive driving model of "information infrastructure-financial inclusion" (H1) and the multi-factor integrated driving model of "information-innovation-inclusion" (H2 and H3). In the dual-factor interactive driving model, information infrastructure provides essential conditions for the expansion, application depth, and digitalization processes of inclusive finance. The development of digital inclusive finance is closely tied to improvements in information infrastructure, equipment upgrades, and the cultivation of information technology talent. This interaction not only supports green innovation with data and technical resources but also promotes efficient resource allocation. By leveraging real-time feedback and consumer data analysis, product innovation is accelerated, supply-demand alignment is optimized, and resource utilization efficiency is enhanced. Hangzhou exemplifies this development model. Initially, Hangzhou relied on digital platforms like Taobao and Alibaba to drive the concentrated growth of its digital industries. This led to significant improvements in the scale and quality of small and medium-sized enterprises. By 2023, Hangzhou's digital trade volume reached 319 billion yuan, accounting for 41.3% of Zhejiang Province's total. Hangzhou also pioneered the formulation of local regulations in digital trade and hosted the third Global Digital Trade Expo. The city achieved significant advancements in the artificial intelligence industry and data factor circulation, contributing to the establishment of "China Vision Valley." Furthermore, Hangzhou introduced the nation's first digital trade statistical system, which supported the optimization of data factor allocation and the widespread adoption of green technologies. These efforts laid a strong foundation for driving new economic momentum and promoting green technological innovation.

In the multifactor intertwined driving paths, the foundational role of digital innovation is critical. The expansion of the digital economy, as a key feature of new productivity, depends on continuous investments in technological innovation. This process has driven breakthroughs and the application of key digital technologies, creating a solid foundation for the deep digitization and informatization of digital inclusive finance. The growing penetration and depth of digital finance, alongside the strengthening of information infrastructure, generate new demands for iterative advancements in digital technologies and expand their application domains. This trend encourages governments to increase investments in digital innovation, promoting technological upgrades within enterprises. In such a market environment, digital innovation energizes green innovation, enabling enterprises to achieve revenue growth while reducing emissions and advancing technologies that enhance market competitiveness. Additionally, the progress of digital inclusive finance and informatization has heightened societal awareness of environmentally friendly enterprises. This competitive pressure further motivates enterprises to engage in green technological innovation. Shanghai exemplifies this dynamic. Its digital economy development spans various fields, including digital finance, data content, the metaverse, intelligent connected vehicles, and smart wearable products, all aimed at deeply integrating digital technologies with the real economy. To support urban digital transformation, Shanghai has established a dedicated fund, providing grants typically covering up to 30% of total project investment. Incentive mechanisms based on assessment results offer individual awards of up to 500,000 yuan. Furthermore, Shanghai has expanded inclusive loan programs for small and micro enterprises, explored characteristic partner banking and insurance mechanisms, developed a comprehensive "credit+" financial service model, and piloted a digital comprehensive service platform for inclusive finance. Suzhou has also excelled in constructing its digital economy, focusing on areas such as digital currency, fintech, and financial big data, aiming to become a leader in digital finance. In terms of financial support, Suzhou offers subsidies of up to 50 million yuan for newly established financial institution headquarters or specialized fintech institutions and provides up to 10 million yuan in funding for digital financial laboratories. In inclusive finance, Suzhou has enhanced its risk-sharing mechanism for technology loans, with a risk compensation ratio of up to 80% for individual projects. It has also introduced inclusive technology insurance, offering premium subsidies of up to 50% for start-ups. These initiatives have driven the high-quality development of Suzhou's digital economy and provided strong financial support for corporate innovation activities.

### 4.4. Robustness Test

To ensure the robustness of the findings, this study conducted an in-depth analysis of the fsQCA (fuzzy-set qualitative comparative analysis) configurations by increasing the PRI consistency threshold to 0.85. Additionally, a lagged dependent variable approach was applied: the one-period lag of "green technological innovation" was used as the outcome variable, and the research period for the digital economy was adjusted to 2015-2022, while keeping other conditions unchanged. The fsQCA configurational analysis was then re-executed with these adjustments.

The results showed that the configurational conditions of the three pathways remained consistent with the findings of the initial analysis. This consistency indicates that, even with adjustments to calibration standards and variable definitions, the influence of digital economy-related indicators on green technological innovation efficiency remains significant. Therefore, the findings of this study have passed the robustness test, confirming the reliability of the results.

## 5. Conclusion and Recommendation

### 5.1. Conclusion

This study systematically reviewed the theoretical relationship between the digital economy and the efficiency of green technological innovation, employing the fsQCA method to explore the configurational antecedents that enhance green technological innovation from the perspective of the digital economy. A multi-factor synergistic pathway was also constructed. The key conclusions are as follows:

The study examined the mechanisms through which the digital economy influences green technological innovation, identifying two primary driving models: the dual-factor interactive model of information infrastructure and inclusive finance, and the multi-factor intertwined model of information, innovation, and inclusiveness. The findings highlighted the critical roles of information infrastructure, digital innovation capability, and the level of inclusive finance in improving green technological innovation efficiency. Additionally, through detailed analysis of various city cases and adjustments to analytical parameters, the stability and reliability of the research findings were further validated. These results confirm that the development of the digital economy significantly stimulates green technological innovation efficiency. To promote green technological innovation and achieve sustainable development, cities should formulate and implement targeted digital economy strategies tailored to their unique developmental characteristics.

### 5.2. Managerial Implications

The implementation of tiered and refined policies with clear execution pathways can enhance the practicality and effectiveness of policy recommendations. This approach provides strong support for the coordinated development of the digital economy and green technological innovation in the Jiangsu-Zhejiang-Shanghai region.

High-efficiency pathway cities should focus on leveraging and deepening their existing advantages. On one hand, these cities can further integrate digital innovation with industrial development. For instance, Shanghai could utilize its digital economy industrial fund to prioritize initiatives that combine green finance and artificial intelligence, accelerating the efficient implementation of green technological innovations. On the other hand, high-efficiency pathway cities should actively strengthen international collaboration and demonstration effects. By leveraging their technological and institutional advantages, these cities can attract global green technology enterprises and investments. For example, Hangzhou could host international green technology expos to showcase its advanced "digital + green" development model, serving as a benchmark for other regions.

Low-efficiency pathway cities should focus on addressing developmental shortcomings. The construction of information infrastructure is a critical issue requiring urgent attention. It is recommended to establish dedicated funds to prioritize the development of fiber-optic networks in rural and economically underdeveloped areas, while collaborating with higher education institutions to establish information technology talent training centers. Additionally, these cities should emphasize the digital transformation of small and medium-sized enterprises (SMEs). Subsidies for digital equipment procurement and operational training programs can help SMEs integrate into the regional digital economy ecosystem. For example, Huai'an could pilot digital financial services to reduce financing barriers for SMEs, thereby stimulating regional economic activity. Furthermore, local governments should collaborate with private capital to establish green technology innovation guidance funds, providing financial support for green research and development in enterprises. For instance, Zhenjiang could leverage such funds to lower entry barriers for enterprises in the green innovation sector, thereby enhancing regional competitiveness.

From a regional collaboration perspective, the Jiangsu-Zhejiang-Shanghai area should establish a coordinated innovation network to enhance resource sharing and technological exchange. A green innovation alliance centered on core cities such as Hangzhou, Shanghai, and Suzhou should be formed, extending its influence to cities like Quzhou and Huai'an. This initiative would facilitate the efficient flow of technology, data, and capital within the region while supporting the establishment of a unified green technology trading platform. Regional low-carbon development pilot projects should be advanced. Underdeveloped cities could implement initiatives such as low-carbon communities and smart industrial parks, with high-efficiency pathway cities providing technical support for these pilots. This collaborative approach would foster mutual benefits and promote sustainable development across the region.

Cities may face several practical challenges when implementing these recommendations, including financial constraints in less developed areas, institutional resistance from traditional industries or local governments, and a lack of technical expertise and human resources. To address these issues, cities can leverage public-private partnerships, seek external funding like green finance initiatives, encourage cross-sector collaboration, and provide targeted incentives such as tax breaks or subsidies. Additionally, partnerships with universities, research institutions, and inter-city knowledge-sharing initiatives can help build the necessary talent and expertise. By proactively tackling these challenges, cities can improve the feasibility and effectiveness of the proposed pathways, driving sustainable green innovation development.

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## Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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