# Configural Pathways of Digital Empowerment for Green Innovation: Evidence from China

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***Abstract:*** *Against the backdrop of sustainable development, green innovation is a strategic choice to achieve the dual goals of economic growth and environmental protection. Using panel data of enterprises from 31 provincial-level regions in China from 2011 to 2022, this study explores the synergistic configuration effects of digital finance, digital transformation, digital infrastructure, and executives' digital background on regional green innovation from a configurational perspective using fsQCA. The findings reveal that digital finance is the most critical condition, as high levels of regional green innovation are largely inseparable from it. Four pathways to enhancing regional green innovation are identified, including a capital-driven path and a multi-factor combination path for green innovation invention patents, as well as a capital-driven path and a dual-element path for green utility model patents. For green innovation invention patents, high-level digital finance is the most significant promoting factor, while digital transformation and executives' digital background require high levels in the multi-factor combination path, but no high-level requirement is observed for digital infrastructure in either path. For green utility model patents, digital finance remains the most significant factor, while executives' digital background plays a certain role in the dual-element path, and neither digital transformation nor digital infrastructure shows high-level requirements. This study investigates the coupling effects of multiple factors and how various digital forms of enterprises influence regional green innovation levels, providing a novel perspective and pathway for green innovation development in regions with low overall digitalization levels and resource-constrained small and medium-sized enterprises.*

***Keywords:*** *Green Innovation, QCA, Digital Finance, Digital Transformation, Executives' Background, Configurational Effects*

## 1. Introduction

Green innovation has become an important choice globally for achieving the dual objectives of economic growth and environmental protection. The growing severity of environmental problems makes concepts such as sustainable development and green innovation increasingly important [1]. Green innovation involves green transformation and upgrades across various stages, including product design, production processes, energy utilization, and waste management, aimed at reducing resource consumption and environmental pollution. As a catalyst, it enhances resource utilization efficiency and reduces carbon emissions [2]. As the driving force behind green development, green innovation promotes high-quality regional economic growth through advanced scientific research or improved industrial processes. It not only effectively replaces traditional end-of-pipe treatment methods but also enables producers to improve pollution management technologies from the source, achieving a win-win outcome for high-quality economic growth and environmental protection.

On April 20, 2023, the White House Office of Science and Technology Policy, the Department of Energy, and the State Department jointly released the "U.S. National Innovation Pathways," aiming to accelerate key technological innovations in clean energy. On March 20, 2024, the European Commission adopted the second strategic plan of the Horizon Europe program, focusing on three key strategic directions: green transition, digital transformation, and building a more resilient, competitive, inclusive, and democratic Europe. Similarly, the Chinese government has emphasized the need for transformative innovation, strengthening technological, policy, and business model innovations to support green transformation and promoting a green and low-carbon technological revolution. Although countries worldwide attach great importance to green innovation, the current situation is not optimistic. According to the "Statistical Analysis Report on Green and Low-Carbon Patents (2024)," only 4.9% of valid invention patents in China in 2023 were related to green and low-carbon technologies. Furthermore, significant disparities exist in the green innovation capabilities of enterprises across different regions, which represents a common global challenge for enterprises in advancing green innovation. Therefore, enhancing green innovation levels remains a critical issue and the future direction for enterprises.

Enterprise green innovation serves as the foundation for achieving sustainable economic development. The core of enterprise green innovation lies in integrating environmental protection concepts into all aspects of product development, production, sales, and services, aiming for efficient resource utilization and minimal environmental pollution. Global economies encourage enterprises to adopt green technologies, green products, and green management practices to enhance their green innovation capabilities. The drivers of enterprise green innovation include government policy guidance, market demand changes, economic incentives, entrepreneurial values, and heightened social responsibility. With the development and application of digitalization, enterprises face both higher demands and better opportunities for achieving green innovation. Leveraging digital technologies to enhance green innovation has become a focal point for global economies.

In academia, green innovation has emerged as a hot research topic, with numerous scholars exploring it from various perspectives. Existing studies have examined the impact of digital industrial agglomeration, digital factor allocation, and the digital economy on regional green innovation. Regarding digital transformation, on the one hand, digital transformation significantly enhances enterprises' green innovation capabilities through "bridges" like internal financing and bank loans [3]. On the other hand, digital transformation may suppress financialization, affecting enterprises' access to funds and thereby hindering green innovation [4]. These debates highlight the complex and multifaceted nature of enterprise green innovation. At the enterprise level, research has explored digital finance, digital transformation, digital infrastructure, and executives' digital backgrounds as factors influencing green innovation[5] [6] [7]. However, existing studies predominantly adopt empirical regression approaches, focusing on linear relationships and examining single-factor impacts on regional green innovation. In reality, green innovation—balancing economic benefits and environmental protection—is a complex, long-term, and systemic project requiring the concurrent consideration of multiple factors. Therefore, exploring the configurational pathways that influence enterprise green innovation becomes crucial. This study employs the Qualitative Comparative Analysis (QCA) method from a configurational perspective to analyze the impacts of various digitalization factors on green innovation at the provincial level. It aims to address the following research questions: Is any single digital factor a necessary condition for regional green innovation? What variable combinations can provide pathways for regional green innovation? Are there substitutive relationships among different configurational pathways? This research contributes to the literature by expanding the understanding of the complex and dynamic interplay of digital factors on regional green innovation, providing theoretical guidance for enhancing regional green innovation capabilities.

China exhibits significant regional disparities in green innovation levels. To explore realistic pathways for achieving high levels of green innovation, this study utilizes panel data of listed enterprises across Chinese provinces from 2011 to 2022 to conduct a QCA analysis. The main findings are as follows: First,Regional green innovation levels are not determined by a single factor but by the coupling of multiple factors.Second,High-level digital finance significantly enhances regional green innovation, especially when digital infrastructure is underdeveloped.Third,High levels of digital finance, digital transformation, and executives' digital backgrounds collectively promote regional green innovation.Forth,High-level digital finance and executives' digital backgrounds can significantly enhance regional green innovation.

The potential marginal contributions of this study include: While previous research predominantly employed linear methods [8] to examine single-factor impacts on regional green innovation, this study uses dynamic QCA to investigate the coupling effects of multiple factors. From the perspective of digital empowerment, this study examines how different digital forms enable enterprises to drive green innovation through configurational synergies.By exploring how different digital forms of enterprises influence regional green innovation, this study bridges the enterprise and regional levels, offering governments insights into leveraging local resources and developing green innovation models suitable for various global contexts.

## 2. Literature review

Existing studies have explored the factors influencing enterprise green innovation. At the government level, local government quality and environmental regulation impact green product innovation and green process innovation. Local government quality plays a significant positive role in the influence of environmental regulation on green product innovation and green process innovation. Improving local government quality and formulating reasonable environmental policies are also crucial for promoting green technological innovation [9]. Moreover, environmental regulations can induce green innovation to promote emission reductions, improve corporate tax burdens and financing constraints, and suppress corporate pollution levels [10]. The intensity of dual-carbon policies positively affects product-oriented and process-oriented green technological innovation, while government financial support moderates the impact of dual-carbon policy intensity on both types of green technological innovation [11]. Green industry policy support reduces the risk of the discontinuation of green technological innovation. Such policies can enhance the stability of green technologies and corporate innovation capabilities, with state-owned enterprises exhibiting higher innovation stability than private enterprises [12]. However, some scholars argue that government interventions do not always yield positive outcomes: while local governments' environmental goal setting enhances urban green technological innovation, inter-city competition can produce negative spatial spillover effects [13]. Government audit reforms, specifically natural resource end-of-tenure audits, significantly hinder corporate performance and reduce innovation investment, thereby negatively affecting enterprise green innovation [14]. Additionally, some scholars have noted that environmental regulation not only fails to promote green innovation but may even inhibit green technological innovation. Digital transformation, by reducing costs, can enhance efficiency under environmental regulation, thereby fostering green technological innovation [15].

At the enterprise and societal levels, the development of internal internet infrastructure within enterprises significantly enhances collaborative green innovation behaviors, as internet technology encourages cooperative green innovation among enterprises [16]. The application of industrial robotics substantially boosts enterprise green innovation, particularly in enterprises with low levels of digital economic development [17]. Furthermore, executives with overseas experience are more willing to take risks and engage in green innovation activities characterized by higher uncertainty, longer investment recovery periods, and higher risks associated with ordinary investments and R&D. Thus, executives with overseas backgrounds can alleviate corporate financing constraints, thereby actively promoting corporate green development and innovation [18]. Digital infrastructure at both the corporate and regional levels can reduce urban carbon emissions. Moreover, digital infrastructure exhibits spatial spillover effects, as local digital infrastructure suppresses carbon emissions in neighboring cities [19]. Digital governance also significantly reduces carbon emissions and plays a crucial role in promoting urban sustainable governance [20]. Green innovation can be divided into two aspects: green product innovation and green process innovation. Corporate social responsibility (CSR) practices significantly promote both green product innovation and green process innovation. Additionally, green dynamic capabilities significantly enhance both aspects of green innovation and mediate the relationship between CSR and green innovation [21]. On the other hand, environmental information disclosure compels listed companies to increase the quantity of green innovation, but it reduces the quality of green innovation [22].

In summary, existing research has analyzed factors influencing enterprise green innovation from various perspectives. However, most studies are based on single-dimensional exploration and investigation, resulting in overly simplistic mechanisms and pathways. This type of research has several limitations: single-factor analyses downplay the interactive relationships among different factors and fail to explore the synergistic relationships and joint mechanisms between variables. Enterprise green innovation, as a balancing node between the economy and the environment, is a complex and diverse systemic project. It cannot be adequately explained by single-factor studies; instead, the overall impact on enterprise green innovation often results from the joint effects of multiple aspects within a mechanism. Therefore, applying the QCA method to study the impacts of various aspects of digitalization on enterprise green innovation offers a novel, comprehensive, and detailed perspective.

## 3. Theoretical analysis

Existing scholars have placed green innovation within the TOE framework to explore the

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synergistic effects of factors such as green technology R&D investment, green technology management capabilities, CEOs' green investment awareness, green technology organizational structures, government green subsidies, and environmental regulations on the green innovation of highly polluting enterprises [23]. Additionally, some scholars have employed the DIIS think tank research theory to construct a three-dimensional model framework for key policy analysis. Furthermore, certain studies have quantitatively analyzed green development policies and trends based on tools, industry development cycles, and technological innovation [24]. Other researchers have entirely approached green innovation from an internal enterprise perspective, exploring the intrinsic mechanisms and contingent conditions between green technological innovation and corporate financial performance [25]. Against this backdrop, this study attempts to analyze green innovation through the lens of digitalization, constructing different configurational analytical frameworks.

Digital finance promotes corporate green innovation. Essentially, digital finance is a novel financing model that leverages information technology to address the high costs and risks associated with traditional financing. First, digital finance significantly promotes regional green innovation by alleviating regional financing constraints and increasing regional R&D investment [26]. Second, digital finance directly fosters corporate innovation by addressing information asymmetry in the green innovation market and analyzing corporate behavior through big data and other digital technologies [27]. Moreover, reducing financial constraints directly impacts corporate green innovation. The alleviation of financing constraints, environmental information disclosure, and increased R&D investment constitute the primary pathways through which digital finance drives green innovation. Digital finance corrects financial resource misallocation and fosters inclusive green innovation across dimensions such as ownership, growth cycles, and corporate scale. By alleviating corporate financing pressures and increasing investment, it enhances corporate risk resilience and promotes green innovation [28]. Digital finance significantly improves high-end green innovation outputs, alleviating the "low-end lock-in" phenomenon in green innovation. Corporate digital finance development mitigates financing constraints and improves internal control levels through internal and external governance structures, thereby promoting high-end green innovation [29]. Furthermore, the relationship between digital finance and corporate green innovation is closely linked to corporate environmental, social, and governance (ESG) performance. Digital finance acts as a catalyst for sustainable technological advancement [30].

Regarding the impact of digital transformation on enterprises, scholars hold varying views. First, digital transformation enhances corporate green innovation capabilities through knowledge sharing [31]. Second, digital transformation promotes green innovation and achieves emission reduction and revenue growth by improving internal control quality and fostering industry-university-research collaboration [32]. Additionally, digital transformation promotes green environmental innovation by increasing R&D expenditure and reducing agency costs. Lastly, digital transformation not only enhances green innovation but also positively impacts the quality of green innovation. Corporate digital transformation attracts executives with experience in digital knowledge innovation and improves intellectual property protection levels [33]. Digital transformation also positively influences revenue and business models through digital orientation [34]. However, digital transformation significantly increases auditing costs, which may inhibit corporate digital transformation efforts [35]. Digital transformation also faces resistance from internal employees [36].

Digital infrastructure serves as the foundation and prerequisite for corporate digital transformation. It is a key engine driving green, low-carbon, and intelligent development in the new era of the digital economy. Digital infrastructure reduces urban carbon emissions, with major cities and non-resource-based cities reaping greater environmental benefits. Digital infrastructure enhances corporate resilience by alleviating financing constraints and promoting business innovation [37]. Moreover, digital infrastructure exhibits spatial spillover effects, as local digital infrastructure suppresses carbon emissions in neighboring cities [19]. The construction of new digital infrastructure indirectly enhances substantive green innovation, finance, entrepreneurial activities, and informatization indices by improving digitalization levels [38]. Digital infrastructure promotes green innovation through key channels such as talent aggregation, increased R&D investment, and industrial structure upgrading [39]. In China, the impacts of digital infrastructure are manifested more concretely. For instance, the "Broadband China" policy indirectly drives green innovation through financialization, increasing corporate revenue and total asset turnover while minimizing management and operational costs. Although the effects vary depending on calendar time, entry cohorts, and exposure duration, most exhibit strong and positive outcomes [40]. Furthermore, digital infrastructure enables governments to enjoy the "dividends" of digitalization while simultaneously feeding back into society and fostering corporate green development and innovation. Digital infrastructure lays a pathway for

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green innovation and development for both the state and enterprises [41].

Executives' experience and background have a significant impact on corporate green innovation. Executives' thoughts and actions often determine a company's business direction and future development. Executives' ESG awareness significantly enhances corporate green innovation, with this effect being more pronounced in companies with lighter pollution, lower financing constraints, and higher marketization levels [42]. Executives with overseas educational backgrounds have a significant positive impact on corporate green innovation [43]. CEOs with IT backgrounds significantly promote digital technological innovation by curbing managerial short-sightedness [44]. Research by Wei, Zhang et al. [45] also confirms that executives with digital backgrounds significantly enhance corporate innovation. Moreover, CEOs with educational or professional experience in digital technologies can elevate corporate digital transformation to higher levels. A CEO's digital technology background significantly drives the digital transformation of high-tech and digital economy enterprises. By promoting digital transformation, CEOs' digital technology backgrounds also substantially improve corporate sustainability [46]. In the new digital landscape, executives' digital cognition and cognitive flexibility positively influence product innovation. Executive cognitive flexibility enhances data-driven dynamic capabilities through high-intensity information search, thereby positively impacting product innovation [47].

## 4. Research methods and data construction

### *4.1 Dynamic QCA*

Traditional QCA methods, limited by theory and tools, primarily use single cross-sectional data for configurational research. However, this traditional approach has a temporal blind spot in theoretical construction, making it difficult to explain complex causal relationships and interactions over time. To address this, this study integrates QCA analysis with panel data to explore the configurational relationships of multiple cross-sectional data under the same temporal effect. Unlike traditional QCA methods, dynamic QCA conducts detection and analysis across three dimensions: inter-group, intra-group, and aggregated levels. Using qualitative comparative analysis, it compares multiple factors to identify the combinations of conditions affecting outcomes and reveals the configurational relationships between factor combinations and results. Through intra-group and aggregated dimensional analysis, the method examines consistency trends between groups.

### *4.2 Variable selection and data sources*

#### *4.2.1 Outcome variable: regional green innovation*

The measurement of regional green innovation in existing literature often involves efficiency calculations using Data Envelopment Analysis (DEA) or its derivatives, such as SBM models, to gauge regional green innovation levels. Some studies also use the volume of authorized green patents in a region to measure green innovation. There is no single standard for measurement. Considering the lag effect of green patent authorizations, this study measures green innovation levels using the number of regional green invention patents and green utility model patents from 2011 to 2022.

#### *4.2.2 Condition variables*

Digital Finance. Digital finance refers to the development and provision of financial services in digital form [48]. Different scholars have adopted various methods to measure digital finance, with no single standard of measurement. Considering authority and comprehensiveness, this study uses the Digital Inclusive Finance Index. Based on statistical data from 2011 to 2022, the study categorizes and calculates data at the provincial level in China to measure the level of digital finance among enterprises in different provinces.

Digital Transformation. Digital transformation refers to significant changes in business models driven by the adoption of digital technologies [49]. Drawing on existing literature, this study uses a frequency-based measurement approach, calculating the occurrence of terms related to digital transformation in corporate reports to assess the level of digital transformation among enterprises in different provinces.

Digital Infrastructure. Digital infrastructure refers to systems that provide digital capabilities such as storage and computation services [50]. Since it is challenging to conduct a detailed investigation of digital infrastructure or pinpoint precise entry points, this study measures digital infrastructure levels by analyzing internet penetration rates in various provinces over different years.

Executives' Digital Background. This refers to executives with digital learning or work experience. This study evaluates the digital level of corporate executives by analyzing data on the number and proportion of executives with digital backgrounds across different years and enterprises.

### *4.3 Variable calibration*

Unlike traditional empirical research, this study employs the dynamic QCA method to analyze and calibrate variables. Specifically, the study determines three thresholds—full membership, crossover point, and full non-membership—based on the size and distribution of variable values, converting raw data into fuzzy membership values ranging from 0 to 1. Following mainstream practices in QCA research [51], this study adopts direct calibration by using the 95th, 50th, and 5th percentiles of variables as anchor points. As is shown in Table 1.

*Table 1. Variable calibration and descriptive statistics*

| variable | | Calibration | | | Descriptive Statistics | | | |
|---|---|---|---|---|---|---|---|---|
| | | Fully subordinate | Intersection | Completely not affiliated | Mean | SD | Min | Max |
| Outcome variable variable | EnvrInvPat | 0.3198 | 0.1946 | 0.0429 | 0.4980 | 0.3017 | 0.02 | 0.99 |
| | EnvrUtyPat | 0.2915 | 0.1749 | 0.0332 | 0.5023 | 0.2977 | 0.03 | 0.99 |
| Dependent variable | Digital | 15.908 | 7.0647 | 2.9772 | 0.4826 | 0.2913 | 0.02 | 1.00 |
| | Internet | 74.4735 | 53.2915 | 46.3647 | 0.4604 | 0.3059 | 0.01 | 0.97 |
| | IT | 0.0635 | 0.0322 | 0.0064 | 0.4868 | 0.3365 | 0.04 | 1.00 |
| | DF | 309.1493 | 238.2869 | 216.4975 | 0.4336 | 0.3202 | 0.01 | 0.96 |

## 5. Empirical analysis

### *5.1 Necessity analysis of single conditions*

When conducting dynamic QCA analysis on panel data, the necessity of single conditions must be determined by combining both consistency and adjusted distance consistency. Typically, a variable is considered a necessary condition for the outcome variable if its consistency exceeds 0.9. Based on aggregated consistency analysis, no condition achieves a consistency value greater than 0.9, indicating that no single variable constitutes a necessary condition and there is no necessary relationship for any single variable. As is shown in Table 2.

*Table 2. Necessity analysis of conditions*

| Conditional Variable | Green innovation invention patents | | Green innovation utility model patent | |
|---|---|---|---|---|
| | Consistency | Coverage | Consistency | Coverage |
| Fdigital | 0.72994 | 0.753359 | 0.670606 | 0.697948 |
| ~Fdigital | 0.589988 | 0.567991 | 0.633806 | 0.615313 |
| Finternet | 0.650282 | 0.703545 | 0.623017 | 0.679723 |
| ~Finternet | 0.653455 | 0.60318 | 0.650568 | 0.605572 |
| Fit | 0.680008 | 0.695779 | 0.630788 | 0.650851 |
| ~Fit | 0.575157 | 0.558237 | 0.613255 | 0.600226 |
| Fdf | 0.682663 | 0.784242 | 0.64999 | 0.752995 |
| ~Fdf | 0.591283 | 0.519961 | 0.618457 | 0.548437 |

### *5.2 Sufficiency analysis of configurations*

The study sets the consistency threshold at 0.9 to ensure explanatory power and sets the RPI (Raw Coverage Index) threshold at 0.7 to eliminate interference. Further, based on differences in core condition variables, two configurational pathways are identified for generating green innovation invention patents and green innovation utility model patents.

The configurational analysis results, as shown in the table, reveal two configurational pathways leading to high-level green innovation invention patents and two configurational pathways leading to

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high-level green innovation utility model patents. In the configurational pathways leading to high-level green innovation invention patents, the overall consistency is 0.8824. For the configurational pathways leading to high-level green innovation utility model patents, the overall consistency is 0.9183. Both values are significantly higher than the minimum threshold of 0.75, indicating that the aggregated consistency provides good explanatory power for the results. As is shown in Table 3.

*Table 3. Results of configurational analysis*

| Conditional variable | Green innovation invention patents | | Green innovation utility model patents | |
|---|---|---|---|---|
| | S1 | S2 | S3 | S4 |
| Fdigital | ⊗ | ● | | ⊗ |
| Finternet | ⊗ | | ⊗ | |
| Fit | | ● | | ● |
| Fdf | ● | ● | ● | ● |
| raw coverage | 0.377631 | 0.55113 | 0.423223 | 0.362212 |
| unique coverage | 0.0913801 | 0.264879 | 0.114315 | 0.0533042 |
| consistency | 0.91668 | 0.907153 | 0.919107 | 0.963938 |
| solution coverage | 0.64251 | | 0.476527 | |
| solution consistency | 0.882494 | | 0.918317 | |

### *5.3 Robustness test*

QCA is a research method based on set theory. This study uses QCA for robustness testing by lowering the consistency threshold to 0.85. The resulting configurations and the overall solution's consistency and coverage remain consistent with the original model, indicating that the research conclusions are robust. As is shown in Table 4.

*Table 4. Robustness test*

| Conditional variable | Green innovation invention | | Green innovation utility model | |
|---|---|---|---|---|
| | S1 | S2 | S3 | S4 |
| Fdigital | ⊗ | ● | | ⊗ |
| Finternet | ⊗ | | ⊗ | |
| Fit | | ● | | ● |
| Fdf | ● | ● | ● | ● |
| raw coverage | 0.377631 | 0.55113 | 0.423223 | 0.362212 |
| unique coverage | 0.0913801 | 0.264879 | 0.114315 | 0.0533042 |
| consistency | 0.91668 | 0.907153 | 0.919107 | 0.963938 |
| solution coverage | 0.64251 | | 0.476527 | |
| solution consistency | 0.882494 | | 0.918317 | |

### *5.4 Analysis of configurational effects types*

#### *5.4.1 Configurational pathways for green innovation invention patents*

In the capital-dominated configurational pathway (S1), characterized by high levels of digital finance and low levels of digital infrastructure and digital transformation, and in the multi-element combinational pathway (S2), characterized by digital finance, executives' digital backgrounds, and digital transformation, the interaction and coupling of single-dimensional demands and multi-dimensional influencing factors jointly affect regional green innovation levels.

In S1, on the supply side, digital finance serves as the core, forming a sufficient condition for high regional green innovation levels when combined with low levels of digital transformation and digital infrastructure. In this configuration, enterprises do not extensively engage in digital transformation, lack robust internet infrastructure, and do not necessarily have executives with IT backgrounds. However, a high level of regional digital finance development (Fdf) drives a high level of green innovation invention patents. This indicates that enterprises with strong internal resources can achieve green innovation even with minimal reliance on internet infrastructure. It also demonstrates that digital finance can play a strong driving role when the degree of digitalization is low.

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In S2, high levels of digital finance, digital transformation, and executives' digital backgrounds collectively contribute to high levels of green innovation invention patents. This suggests that enterprises with high digitalization levels and executives with IT backgrounds can achieve green innovation through the combination of internal resources and external financial support, even when internet penetration rates are low.

#### *5.4.2 Configurational pathways for green innovation utility model patents*

Considering the potential asymmetrical causal relationships arising from the coupling and interaction of influencing factors, this study further explores the pathways for forming regional green innovation utility model patents. In the capital-dominated configurational pathway (S3), high levels of digital finance combined with low levels of digital infrastructure lead to high levels of green innovation utility model patents. This suggests that, even when enterprises lack digitalization and internet infrastructure, digital finance can serve as a critical resource for promoting utility model patent innovation. Moreover, low levels of digitalization can inversely enhance the driving role of digital finance in regional green innovation.

In the dual-element configurational pathway (S4), high levels of digital finance and executives' digital backgrounds, combined with low levels of digital transformation, result in high levels of green innovation utility model patents. This indicates that enterprises, through executives' technical knowledge and leadership, can mobilize resources via digital finance channels to promote green innovation, even with limited support from digital resources.

#### *5.4.3 Potential substitutive relationships among configurations*

By comparing the configurational pathways for green innovation invention patents in S1 and S2, the potential substitutive relationships between high regional green innovation invention patent configurations can be uncovered. The formation conditions of S1 and S2 indicate that, when regional digital finance levels are high, low levels of digital transformation and digital infrastructure can substitute for high levels of digital transformation and executives' digital backgrounds.

Similarly, by comparing the configurational pathways for green innovation utility model patents in S3 and S4, the potential substitutive relationships between high regional green innovation utility model patent configurations can be identified. The formation conditions of S3 and S4 suggest that, under the support of high levels of regional digital finance, low levels of digital infrastructure combined with high levels of executives' digital backgrounds and low levels of digital transformation can be mutually substitutive.

### *5.5 Group-level results*

Analysis reveals that in both the configurational pathways for green innovation invention patents and green innovation utility model patents, S1 and S3 demonstrate the strong driving role of digital finance, supported by a robust digital finance system. A representative province is Jiangsu, which has a solid industrial base dominated by manufacturing. However, in recent years, Jiangsu's numerous small and medium-sized enterprises (SMEs) have faced constraints in funding, technology, and talent during the process of digital transformation. Compared to large enterprises, SMEs face greater difficulties in adopting advanced digital technologies and building intelligent production systems. First, SMEs encounter resource limitations, network security issues, and ongoing challenges from rapid technological change [52]. Second, SMEs often lack sufficient awareness and strategic planning for digital transformation, leading to a lack of systematic and sustained transformation efforts. This has resulted in lower digitalization levels and slower progress in digital transformation for many traditional manufacturing enterprises within the province.

However, the Jiangsu government has placed significant emphasis on developing digital finance, forming a relatively mature digital finance ecosystem. Through financial policies, funding support, and green financial products, it has provided innovative support for enterprises. For example, some green innovation enterprises in Jiangsu, such as those in new energy and environmental technology, have obtained low-cost funding via digital finance platforms, which has increased their R&D investment and accelerated technological innovation and commercialization [26]. Digital finance promotes the development of green finance, providing more financing channels for green innovation projects while significantly reducing corporate debt financing costs [53].

Even enterprises without strong digital backgrounds or digital capabilities can leverage a robust digital finance system to access sufficient funds for innovation and R&D. For instance, through green financial loans and government policy support, enterprises can fund research and breakthroughs in energy conservation, emission reduction, and pollution control technologies, thereby driving green innovation [54]. This aligns with institutional theory and external support dependency theory, wherein external financial support compensates for enterprises' internal deficiencies in digital capabilities and infrastructure.

Both the configuration of high digital finance development with low levels of digital transformation and digital infrastructure (S1) and the configuration of high digital finance development with low levels of digital infrastructure (S3) suggest that in regions with relatively lagging digitalization, digital finance can serve as a crucial driver of economic development and innovation. Due to the limitations of traditional financial services, enterprises and individuals in these regions are often more eager to adopt digital financial solutions to meet their financing, payment, and risk management needs. This demand may stimulate innovation in digital finance, driving financial institutions and technology companies to develop digital financial products and services tailored to local needs. Consequently, even with low levels of digital transformation and digital infrastructure, these regions may have large potential user bases. The convenience and inclusivity of digital finance allow for easier financial access and payment processes [55], which facilitates its rapid penetration and adoption, leading to overall high levels of green innovation.

In the configurational pathway for green innovation invention patents (S2), high digital finance support, executives with strong digital backgrounds, and a solid foundation of digital transformation are evident. Beijing is a representative of this pathway. As China's capital and a hub for technology and innovation, the Beijing government has emphasized the development of digital finance by formulating various policy documents to guide and regulate the healthy development of the digital finance industry. These policies have significantly stimulated the growth of the information industry, improved the business environment, and positively influenced the development of digital finance [56]. For example, documents such as the Beijing Opinions on Promoting High-Quality Development of Digital Finance outline the goals, pathways, and key tasks for digital finance development. Beijing has also completed China's first five-year plan for financial technology innovation and launched national-level financial technology and digital finance demonstration zones, significantly advancing the digital finance landscape.

For instance, the Bank of Beijing, a pioneer in digital transformation, has achieved significant results in IT investment, talent development, and technology applications. By launching innovative products like the AIB Financial Intelligence Application Platform, the bank has comprehensively enhanced the intelligence of its financial services, offering more convenient and efficient services to its customers. Additionally, the bank has empowered its risk management system through digital transformation, resulting in a sustained decrease in non-performing loan rates.

Beijing-based enterprises are also leading the country in digital transformation. Many have not only achieved automation and informatization but are also actively adopting cutting-edge technologies like big data. For example, the collaboration between Beijing Unicom and Jingneng Group demonstrates how digital transformation drives business innovation and transformation. Beijing Unicom provided top-level digital transformation planning and related technical services to Jingneng Group, helping it formulate its "14th Five-Year" digital transformation strategy. This project accelerated Jingneng Group's infrastructure construction, enhanced its comprehensive digital governance capabilities, and achieved intelligent and efficient business operations. Furthermore, this collaboration has advanced the digital transformation of the energy industry, providing a model for other sectors.

As a gathering place for high-tech talent, Beijing has numerous enterprises led by executives with strong digital backgrounds, technical expertise, and management capabilities. These leaders can effectively leverage digital technologies to achieve green innovation. Although Beijing's digital infrastructure is not particularly prominent, enterprises can independently utilize their digital resources to drive green innovation through high levels of corporate digitalization, IT-experienced executives, and robust digital finance support. This aligns with the human capital theory, providing a new perspective on green innovation, where human capital indirectly fosters inclusive green development. The interaction between digital inclusive finance and human capital promotes inclusive green development [57].

In the configurational pathway for green innovation utility model patents (S4), enterprises have weaker digital transformation capabilities, but executives with digital backgrounds and high levels of regional digital finance support compensate for this. Digital infrastructure is not a key factor in this pathway. This suggests that even with low levels of corporate digitalization, high digital finance and

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executives with digital expertise can still drive innovation in green utility model patents. Shandong is a representative province of this pathway. In recent years, cities like Qingdao have experienced rapid development, becoming international metropolises that attract high-tech talent. Shandong also has a comprehensive digital training system established by universities, training institutions, and enterprises, which helps executives develop their digital capabilities.

Shandong has explicitly proposed the goal of becoming a "digitally strong province," providing policy support for enhancing executives' digital backgrounds. For instance, the Shandong Provincial Big Data Bureau has promoted digital technology applications and stimulated executives' enthusiasm for digital transformation through initiatives like selecting outstanding applications for the "Digital Shandong Standards." However, traditional industries in Shandong, especially SMEs, often have entrenched business models that are difficult to transform fully. SMEs face significant obstacles such as limited funding, IT security challenges, and a shortage of external labor market experts, which hinder their digital transformation efforts [58].

Despite these challenges, Shandong maintains high levels of green innovation utility model patents, which can be explained by the substitution theory of leadership. Executives' digital backgrounds compensate for deficiencies in corporate digitalization. Compared to comprehensive digital transformation, this "non-digital" innovation model is more flexible, relying on executives' decisions and technical expertise rather than large-scale information systems. This model provides a new transitional approach for resource-constrained small enterprises.

## 6. Conclusions and policy implications

Using panel data from 31 provinces (municipalities and autonomous regions) in China from 2011 to 2022, this study applies dynamic QCA to uncover the core influencing factors and the coupling relationships affecting provincial-level green innovation in China. Two configurational pathways lead to high levels of green innovation invention patents, and two lead to high levels of green innovation utility model patents. In the configurational pathways for green innovation invention patents, regional high-level digital finance development is the most significant factor. Digital transformation and executives' digital backgrounds are critical in S2, while neither pathway requires high levels of digital infrastructure. In the configurational pathways for green innovation utility model patents, regional high-level digital finance remains the most significant factor. High levels of executives' digital backgrounds play a role in S4, whereas digital transformation and digital infrastructure are not critical.

The policy recommendations in this article are as follows: Governments should focus on synergistic effects, clearly identifying regional resource endowments and leveraging interactions among variables to explore localized green innovation models instead of applying templates.

Given the importance of digital finance, governments should actively support and regulate digital finance institutions, promoting mobile payments and digital credit while integrating digital elements into financial services to stimulate regional green innovation.

Enterprises should embrace digital finance policies, actively pursue digital transformation, and enhance executives' digital literacy and innovation capabilities. Tailored measures should be adopted for different types of green innovation projects to better meet their specific needs and development characteristics.

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