

Beyond the single thread: how organisational, technological, and environmental factors jointly shape green patent persistence in textile firms

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ABSTRACT – REZUMAT

Beyond the single thread: how organisational, technological, and environmental factors jointly shape green patent persistence in textile firms

As one of the most resource-intensive and polluting manufacturing industries, the textile sector's sustained green patenting activities are garnering increasing attention. This study investigates 48 Chinese A-share listed textile enterprises, employing a combined Necessity Condition Analysis (NCA) and fuzzy-set Qualitative Comparative Analysis (fsQCA) approach. We systematically explore how five antecedent conditions, firm size, executive educational background, digital transformation, media attention, and government subsidies, collectively influence the sustained green patent application performance of textile enterprises through various configurations. The results show that no single factor qualifies as a necessary condition; rather, sustained green patenting emerges from asymmetric combinations of factors. Media attention and government subsidies appear as common core elements across configurations associated with high levels of sustained green patenting. We identify two high-performance pathways: an "environment-dominated-organisational collaboration" pathway and a "technology-environment-driven" pathway. Conversely, we uncover four pathways associated with low sustained green patenting: "environmental deficiency", "technological inadequacy", "organisational weakness", and "single-factor presence". Overall, the study elucidates the complex causal configurations shaping sustained green patenting in textile firms and offers implications for the industry's sustainable development.

Keywords: textile industry, sustained green patent applications, socio-ecological systems theory, fsQCA

Dincolo de o singură perspectivă: modul în care factorii organizaționali, tehnologici și de mediu modelează împreună persistența brevetelor ecologice în firmele textile

Fiind una dintre industriile manufacturiere cu cel mai mare consum de resurse și cele mai poluante, activitățile de brevetare ecologică susținută ale sectorului textil atrag din ce în ce mai multă atenție. Acest studiu analizează 48 de întreprinderi textile din China listate la bursă, utilizând o abordare combinată de analiză a condițiilor de necesitate (NCA) și analiză comparativă calitativă fuzzy (fsQCA). Explorăm în mod sistematic modul în care cinci condiții antecedente, dimensiunea întreprinderii, nivelul de studii al conducerii, transformarea digitală, atenția mass-media și subvențiile guvernamentale, influențează în mod colectiv performanța susținută a întreprinderilor textile în materie de cereri de brevete ecologice prin diverse configurații. Rezultatele arată că niciun factor nu poate fi considerat o condiție necesară; mai degrabă, brevetarea ecologică susținută rezultă din combinații asimetrice de factori. Atenția mass-media și subvențiile guvernamentale apar ca elemente comune de bază în toate configurațiile asociate cu niveluri ridicate de brevetare ecologică susținută. Identificăm două căi de performanță ridicată: o cale „de colaborare organizațională – dominată de mediu” și o cale „determinată de tehnologie-mediu”. În schimb, descoperim patru căi asociate cu un nivel scăzut de brevetare ecologică susținută: „deficiență de mediu”, „inadecvare tehnologică”, „slăbiciune organizațională” și „prezența unui singur factor”. În ansamblu, studiul elucidează configurațiile cauzale complexe care modelează brevetarea ecologică susținută în întreprinderile textile și oferă implicații pentru dezvoltarea durabilă a industriei.

Cuvinte-cheie: industria textilă, cereri susținute de brevete ecologice, teoria sistemelor socio-ecologice, fsQCA

INTRODUCTION

The textile industry is a cornerstone of the global economy, not only creating vast employment opportunities but also making significant contributions to the economic growth of many countries. However, with the rise of fast fashion and the proliferation of overproduction and consumption, the industry has increasingly exposed serious issues of resource waste and environmental pollution [1]. In the production phase, textile manufacturing is highly dependent

on energy and water resources, and the emission of various harmful substances poses a threat to both the ecological environment and the health of local communities. Furthermore, the industry faces social sustainability challenges, such as low wages, insufficient human rights protection, and poor working conditions for workers [2–4].

According to relevant statistics, approximately 92 million tons of textile waste are generated each year, yet only about 20% is collected for recycling or reuse. The proportion of recycled materials used for new

production is a mere 0.3%. In addition, some studies predict that by 2050, global textile consumption will triple and could account for more than a quarter of total global carbon dioxide (CO₂) emissions. Given this mounting pressure for sustainable development, textile firms must proactively adjust their traditional business models and accelerate the transition towards a greener and more sustainable approach to ensure long-term viability [5].

To address these challenges, green innovation has emerged as a critical pathway for textile companies to achieve environmental transformation. As a typical manufacturing sector with high resource consumption and concentrated pollution, the textile industry faces increasingly stringent environmental regulations and fierce market competition. To genuinely improve their environmental performance, firms must continuously engage in relevant innovation activities [6]. Unlike one-off or phased green initiatives, continuous green innovation emphasises a long-term commitment of resources to progressively optimise environmental technologies and production processes. This sustained effort not only helps firms effectively reduce their environmental footprint and meet regulatory and societal expectations but, more importantly, it significantly enhances their long-term competitiveness. By consistently investing in green innovation, firms can achieve continuous cost reductions, improve resource efficiency, and foster product differentiation, thereby securing a favourable position in a competitive market [7]. Therefore, an in-depth exploration of the drivers of continuous green innovation in textile firms and their underlying mechanisms holds significant theoretical and practical value.

To help firms achieve continuous green innovation, existing research has explored its influencing factors from multiple perspectives [8, 9]. Internally, some scholars argue that larger firms with more abundant resources and capabilities are better positioned for continuous green innovation [10, 11]. However, other studies have found that due to complex organisational structures and high coordination costs, medium-to-large enterprises may exhibit path dependence and slow reactions when pursuing green innovation [12]. Externally, evidence shows that firms located in regions with strict environmental regulations generally achieve a higher level of green innovation [13]. Yet, where formal institutional constraints are weak, informal mechanisms like media supervision can serve as an effective supplement, indirectly encouraging firms to improve green innovation by increasing information transparency and public pressure [14].

It is noteworthy that existing studies on the drivers of continuous green innovation have largely adopted a single-factor approach, leading to inconsistent conclusions. This inconsistency may stem from a traditional research paradigm that fails to fully capture the complex interactions among influencing factors [15]. Currently, most mainstream research on continuous green innovation relies on linear regression models, which tend to analyse the “net effect” of variables.

This makes it difficult to capture their complementarity, substitutability, and asymmetry [15]. Such a narrow perspective not only hinders a comprehensive understanding of the complex mechanisms at play but also limits the provision of systematic and effective guidance for business practice [16].

Social ecological systems theory posits that individuals and their social environment form a social ecosystem where various subsystems are interconnected and interact with one another. As a key component of this ecosystem, a firm's actions and outcomes are also interrelated with various systemic elements [17]. Furthermore, from a practical standpoint, advancing continuous green innovation is a complex systemic endeavour influenced by both a firm's internal characteristics and external institutional and social factors [18]. Therefore, it is essential to study continuous green innovation within the broader social ecosystem to understand how different environmental elements can synergistically align to drive textile firms towards this goal.

Qualitative Comparative Analysis (QCA) is an effective method for addressing causal complexity and offers significant advantages for this purpose. QCA emphasises the interaction among antecedent conditions rather than their isolated existence, focusing on the holistic effect of condition combinations. This approach can provide a deeper understanding of the causal mechanisms of continuous green innovation. Moreover, QCA can identify multiple configurations of sufficient conditions leading to the same outcome and test for causal asymmetry between high and low outcomes. This capability allows for a clear depiction of the diverse pathways textile firms can take to achieve continuous green innovation and the underlying logic of each path.

China provides a unique and representative research context. As the world's largest producer and consumer of textiles, its industry is vast and its supply chain is highly comprehensive, spanning from raw material sourcing, spinning and weaving, and garment manufacturing to final sales. This provides a rich pool of industry practice and data. According to 2025 statistics, China generates approximately 20 million tons of textile waste annually, ranking first globally. This massive waste output creates a more urgent need for the Chinese textile industry to transform, particularly in improving resource efficiency, comprehensive waste management, and green innovation practices.

Furthermore, the Chinese textile industry has faced increasingly strict environmental policies and industrial restructuring measures in recent years. In September 2020, the Chinese government officially announced its “carbon peaking and carbon neutrality” goals at the 75th United Nations General Assembly, with targets to peak CO₂ emissions before 2030 and achieve carbon neutrality before 2060 [19, 20]. Following this announcement, the textile industry, as a high-carbon emitter, has quickly become a key focus for policy regulation and green

transformation. For instance, the Implementation Plan for Clean Production Transformation in Key Industries, enacted in 2023, further requires textile firms to fully adopt clean production technologies in high-energy consumption stages like printing, dyeing, and chemical fibre production.

Based on this analysis, we aim to address three key research questions: (1) Is there any single factor that is a necessary condition for continuous green patent applications in textile firms? (2) Which combinations of factors lead to high or low levels of continuous green patent applications in textile firms? (3) Which potential factors should policymakers pay attention to? Through our exploration of these questions, we seek to uncover the complex causal relationships behind continuous green patent applications in textile firms and provide substantive guidance and suggestions for understanding the drivers of green innovation from a configurational perspective.

This study contributes to the extant literature in two main ways. First, our research departs from the traditional statistical paradigm of analysing the net effect of single variables [10, 21–23]. While previous studies mainly relied on traditional models to analyse the isolated influence of individual factors, they lacked an exploration of how different factors combine and substitute for one another to drive continuous green innovation. Drawing on a set-theoretic perspective [24], we adopt a configurational approach to view continuous green patent applications as the result of multiple interacting factors. This reveals how different combinations of conditions jointly drive a firm's green innovation performance through synergistic or substitutive mechanisms. The introduction of this perspective effectively addresses the shortcomings of existing research in explaining the nonlinear relationships among variables. Second, by comparing the configurational pathways for high and low levels of continuous green innovation in textile firms, we confirm the presence of causal asymmetry. That is, the combinations of conditions that lead to high-level innovation cannot simply be inverted to explain the causes of low-level innovation. This finding provides new empirical evidence for refining the theoretical framework of continuous green innovation.

THEORETICAL FOUNDATION AND MODEL CONSTRUCTION

Theoretical foundation

Social-ecological systems theory provides a framework for systematically analysing the interactions between individuals and their environments, emphasising that individual behaviour is influenced by multi-level environmental factors collectively. This theory segments ecosystems into three layers: the micro-level, focused on the individual; the meso-level, involving small groups directly linked to the individual, like families and organisations; and the macro-level, encompassing broader social constructs such as culture, institutions, and policy frameworks.

Through dynamic interactions at these hierarchical levels, social-ecological systems shape individual behaviours and decisions [17].

Recently, researchers have begun applying social-ecological systems theory to organisational studies, suggesting that enterprises are also immersed within multi-level environmental systems, influenced by factors from various levels. An enterprise's capabilities and behaviours (micro-level), industry and regional pressures (meso-level), along with market competition dynamics and regulatory policies (macro-level), can all impact corporate innovation [25, 26].

Therefore, when analysing corporate green innovation, it is vital to situate it within the broader social-ecological system, identifying the collaborative effects among environmental factors at various levels. This theory offers an ideal analytical framework and structural foundation for understanding diverse mechanisms that drive organisational innovation.

Model construction

As previously discussed, a firm's continuous green innovation is not influenced by isolated system elements but rather through a synergistic mechanism, resulting in a nonlinear, interactive, and equifinal relationship among factors. This complexity makes it difficult for traditional linear regression models to fully capture the combined effects of multiple variables. In contrast, fuzzy-set qualitative comparative analysis (fsQCA) is uniquely suited for this task. It can identify multiple configurational paths to a single outcome and simultaneously characterise the complementarity and substitutability among condition variables, making it ideal for analysing the multi-level drivers of corporate green innovation within a social ecological system framework.

From the micro-level, the size of an enterprise is a crucial internal structural characteristic influencing its green innovation capabilities. The textile industry is typically resource-intensive and highly polluting, where green innovation requires substantial capital investment and long-term technological accumulation. According to Schumpeter's hypothesis, in contexts where capital markets are imperfect [27, 28], larger organizations are more likely to gain external financing, providing them with superior financial capacity and risk tolerance. This enables continuous investment in the development of green dyeing technologies, upgrading of environmental equipment, and the establishment of energy-saving and emission-reduction systems, subsequently enhancing their sustained green innovation levels [10, 11]. Additionally, large textile companies often have mature management systems, standardised production processes, and strict adherence to environmental compliance, allowing them to effectively implement green production techniques and enhance the efficiency of organisational execution in green innovation. However, research also points out that medium and large enterprises may face organisational inertia during green innovation. Complex internal structures with multiple layers can slow down

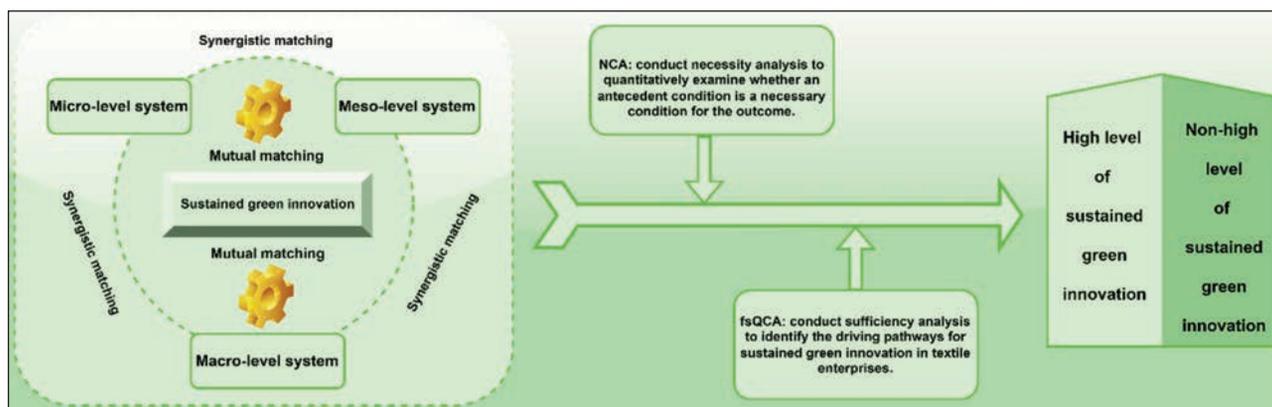


Fig. 1. Theoretical framework

decision-making related to green technologies and resource allocation, while increasing communication and coordination costs might reduce project execution efficiency, thereby impairing the agility and adaptability of green innovation [12].

From the meso-level perspective, digital transformation and executive academic backgrounds are increasingly crucial in promoting sustained green innovation. As enterprises seek to improve green processes, smart manufacturing, and clean production, they need digital technologies to enhance resource allocation efficiency and environmental management capabilities. Digital technologies provide transparency and visualisation that help reduce internal operational and coordination costs and significantly lower external transaction costs, such as those related to search, negotiation, and supervision in green supply chain management [29]. For instance, using IoT, big data, and smart sensors, textile enterprises can monitor energy use and emissions in dyeing processes in real time, improving control and responsiveness in green production [30]. Moreover, Upper Echelons Theory indicates that executives play a pivotal role in strategic planning and resource allocation decisions, with their educational backgrounds and cognitive levels directly affecting the organisation's innovation focus and environmental strategy choices. In the textile sector, managers with higher education backgrounds are more likely to possess systemic thinking and foresight, enabling them to understand green development trends, introduce advanced green management concepts and digital tools, and drive exploration and advancements in green dyeing technology, wastewater recycling, and green certification systems to enhance sustainable green innovation capacity.

From the macro-level perspective, sustained green innovation in enterprises is influenced by external environmental factors, including supervisory pressure and policy frameworks. New Institutional Economics suggests that in environments where government enforcement is inadequate or regulatory systems are underdeveloped, media oversight can serve as an effective alternative institutional constraint [14]. In the textile industry, media often exposes issues like excessive wastewater discharge and

non-compliance in chemical dye usage, prompting enterprises to maintain legal compliance and social reputation by adopting green materials and creating eco-friendly products [31, 32]. However, some studies highlight that under strong social supervision pressure, some textile firms may prefer short-term reactive measures, such as temporarily acquiring pollution control equipment or upgrading emission monitoring systems, rather than investing in longer-term, high-risk green technology research and development [33]. Additionally, policy support, particularly government subsidies, is becoming a vital external resource in driving green transformation in textile enterprises. According to signalling theory, green subsidies not only alleviate initial financial pressures but also release positive signals about the enterprise's commitment to green governance, attracting further financial resources and commercial cooperation opportunities [34]. This ensures that enterprises have sufficient funds for green innovation and sustainable production.

In conclusion, integrating social-ecological systems theory, we identify five antecedent conditions from the micro, meso, and macro contexts: enterprise size, digital transformation, executive academic backgrounds, media pressure, and government subsidies. These conditions are used to construct a configurational analysis framework for sustained green patent applications in textile companies. The detailed research framework is shown in figure 1.

RESEARCH DESIGN

Research methods

Necessary Condition Analysis (NCA)

NCA is a tool used to identify and quantify whether a variable is a necessary condition for a particular outcome. Unlike fuzzy set qualitative comparative analysis (QCA), which assesses conditions based on set relations, NCA specifies the minimum level a variable must reach to achieve a specific outcome [35]. This method highlights how conditions constrain results by calculating effect sizes and identifying bottleneck points. In practice, the "NCA" package in R-Studio provides ceiling regression (CR) and ceiling envelope (CE) methods for continuous and discrete variables,

respectively. Determining necessary conditions using NCA requires an effect size (d) greater than 0.1 and significance verified through a Monte Carlo simulation permutation test ($p < 0.05$).

Fuzzy Set Qualitative Comparative Analysis (fsQCA) QCA is a set-theoretic and Boolean-based method that treats cases as members of different condition sets. By measuring each case's "membership score" within these sets, it reveals the complex causal relationships between condition combinations and the outcome. Unlike traditional binary logic, fsQCA allows for variable membership to range from 0 to 1, capturing the gradual and nuanced nature of real-world conditions. This method is widely used in management and social sciences to identify "necessary" and "sufficient" conditions, which help uncover multi-causal pathways and causal asymmetry [30].

We chose fsQCA for the following reasons. First, a firm's continuous green innovation is influenced by a complex interplay of factors, leading to nonlinear relationships, multiple causal paths, and causal asymmetry [36, 37]. Traditional linear models, which focus on the independent net effect of variables, are ill-equipped to capture these complexities. fsQCA, by analysing the necessity and sufficiency of condition combinations, can reveal how multiple, distinct configurations lead to the same outcome, thus fully capturing the interactions, complementarity, and substitutability among variables. Second, fsQCA allows conditions to have varying degrees of membership, which provides a more granular reflection of the strength and relative importance of different factors. This makes it particularly suitable for studying complex, multi-dimensional phenomena. Finally, fsQCA is well-suited for small-to-medium sample sizes. Our sample of 48 cases is an ideal size for using this method to conduct an in-depth configurational analysis, rather than relying on traditional large-sample linear inference.

Variable selection and data sources

Following the China Securities Regulatory Commission's 2012 industry classification standards, we selected textile companies listed on Shanghai and Shenzhen A-shares in 2024 as our research subjects. During sample selection, ST and *ST companies and those missing key data were excluded, resulting in a sample of 48 listed textile companies. Annual reports were sourced from official websites of the Shenzhen Stock Exchange and Shanghai Stock Exchange, media attention data came from the CNRDS database, and financial data was retrieved from the CSMAR database. Given the lag effect in sustained green innovation, antecedent conditions were lagged by one period.

Variable measurement and calibration

Outcome variable

Our outcome variable is the continuous green patent application of firms. As a preliminary step, we first need to measure green innovation itself. Patents are a widely used and reliable proxy for innovation output,

as they represent specific, quantifiable achievements that possess originality, uniqueness, and market competitiveness. They are easily evaluated and compared due to their relatively uniform global standards, and they directly reflect a firm's innovation performance and development trends.

To identify green patents, we screened the patent application information of our sample firms from the website of the China National Intellectual Property Administration, using the "IPC Green List" developed by the World Intellectual Property Organisation. We then use the number of green patent applications as our measure of green innovation.

Consistent with previous research [6], we measure the level of continuous green innovation by comparing green patent applications across consecutive periods to reflect the sustainability of a firm's innovation efforts. The specific formula is as follows:

$$OIP_t = \frac{Patent_t + Patent_{t-1}}{Patent_{t-1} + Patent_{t-2}} \times (Patent_t + Patent_{t-1}) \quad (1)$$

here, OIP_t represents the continuity of a firm's innovation output in year t , while $Patent_{t-2}$, $Patent_{t-1}$, and $Patent_{i,t}$ denote the number of green patent applications for firm i in years $t-2$, $t-1$, and t , respectively.

Micro system

Enterprise Size: Enterprise size can be measured in various ways, such as employee count, assets total, profits, and revenue. We followed mainstream studies employing the natural logarithm of total assets for this measurement [38, 39].

Meso system

Digital Transformation and Executive Educational Backgrounds: For digital transformation, following Wu et al. [40], we employ text analysis to measure corporate digital transformation. First, the core of digital transformation behaviour is defined as the "application of foundational technologies" and the "implementation of technological practices". The application of foundational technologies encompasses four typical digital transformation technologies: artificial intelligence (A), blockchain (B), cloud computing (C), and big data (D). The implementation of technological practices (E) is categorised based on their practical application. Figure 2 presents the keyword map. Second, utilising a dataset compiled by extracting text from the annual reports of the sample firms using Python, keywords from figure 2 are searched, matched, and counted for frequency. These frequencies are then aggregated by key technological category to form a final summed word frequency, thus constructing the digital transformation indicator system for firms. Finally, we apply a logarithmic transformation to the total word frequency to derive the overall indicator measuring a firm's digital transformation. On the other hand, we measure executive education level using the ratio of the total education level scores of listed company executives to the number of executives. In the CSMAR database, executive educational backgrounds are classified as follows: 1 = Technical/Vocational Secondary School and

below, 2 = Associate Degree (Junior College), 3 = Bachelor's Degree, 4 = Master's Degree, 5 = Doctoral Degree, 6 = Other.

Macro system

Media Attention and Government Subsidies: Media attention is quantified by annual media coverage, including online and print reports. Government subsidies are measured by direct fiscal support, adjusted by adding one and taking the logarithm.

We used quantiles for calibrating data according to mainstream studies [36, 41], setting full membership thresholds, crossover points, and full non-membership thresholds at the 95%, 50%, and 5% quantiles of the case data.

EMPIRICAL ANALYSIS

Analysis of necessary conditions

Before conducting QCA, we test whether individual factors constitute necessary conditions for high levels of continuous green patent applications. We import the calibrated fuzzy-set data into R-Studio to perform

necessity tests for each antecedent condition. The NCA results indicate that the necessity of executive educational background and government subsidies is statistically insignificant (P-value > 0.05), meaning neither condition is individually necessary for the outcome. Although firm size, digital transformation, and media attention are statistically significant (P-value < 0.05), their effect sizes (d) are all below 0.1, and thus none constitutes a necessary condition for the outcome.

Furthermore, we examine the necessity bottleneck levels for each condition. Table 1 reveals that achieving a 100% level of continuous green innovation requires a firm size level of 9.6%, a digital transformation level of 1%, an executive education level of 1%, a media attention level of 5.3%, and a government subsidy level of 7.9%.

To further confirm the robustness of these findings, we conducted a necessity analysis using fsQCA 3.0 software. Generally, a necessary condition must have a consistency score of at least 0.9 [41]. The consistency scores for each antecedent condition

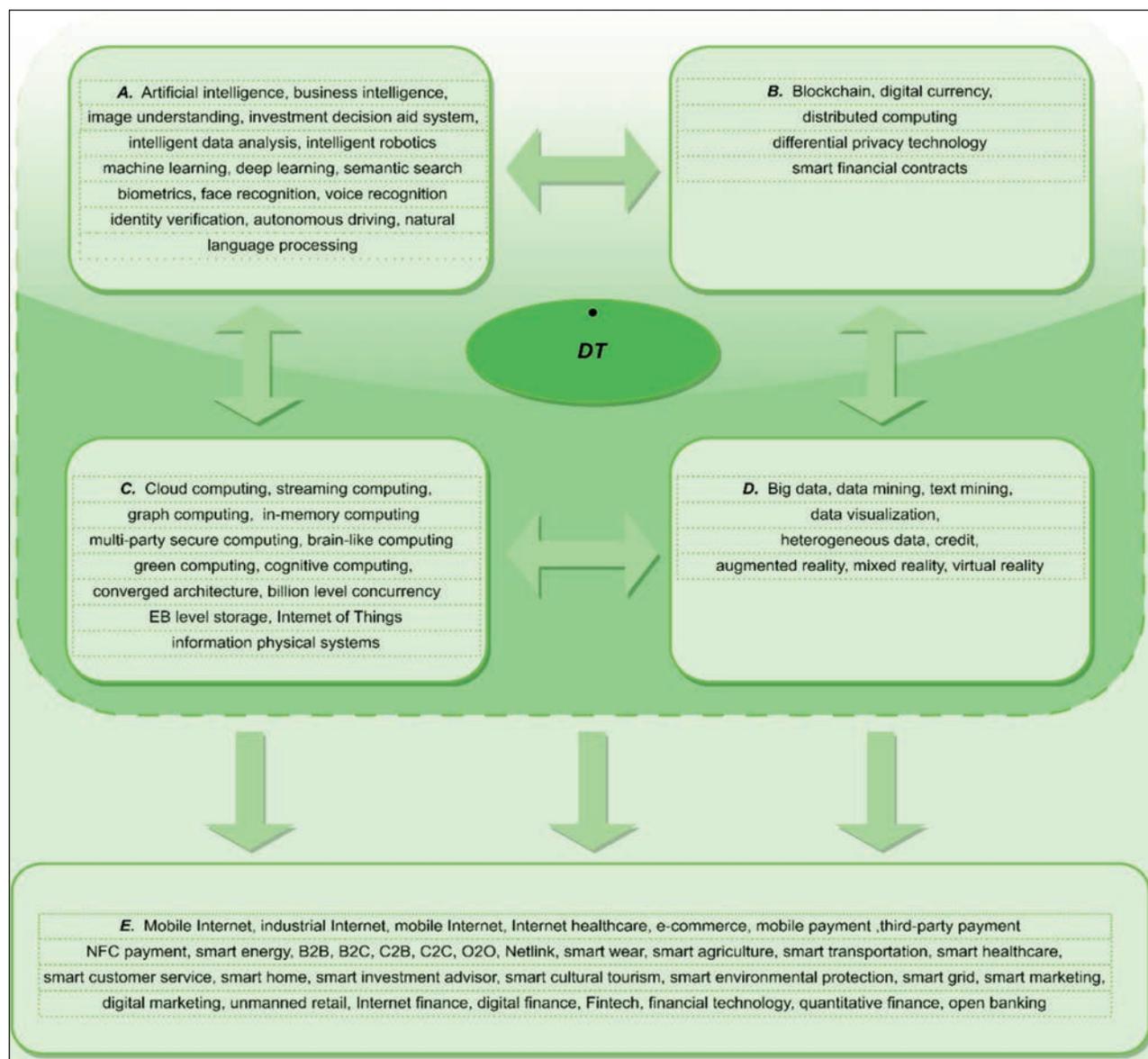


Fig. 2. Characteristic keyword map

ANALYSIS RESULTS OF BOTTLENECK LEVEL IN NCA METHOD (%)					
Sustained green innovation	Firm size	Digital transformation	Executive educational attainment	Media attention	Government subsidies
0	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN
30	NN	NN	NN	NN	NN
40	NN	NN	NN	NN	NN
50	NN	NN	NN	NN	NN
60	NN	NN	NN	NN	NN
70	4.4	NN	NN	NN	NN
80	6.1	NN	NN	NN	1.5
90	7.9	NN	NN	3.9	4.2
100	9.6	1	1	5.3	7.9

Note: The table uses a cap regression analysis CR; NN indicates not necessary.

and its complement fell below this 0.9 threshold. This robustly confirms that no single factor is, by itself, a necessary condition for improving a textile firm's continuous green patent applications.

This finding carries significant economic implications. It suggests that continuous green innovation in the textile industry is not driven by a single factor in isolation but is instead a product of inherent synergy. In other words, firms require an organic combination of multiple conditions to effectively foster the sustained development of green innovation. This result implies that managers should focus on the systematic coordination of various influencing factors rather than strengthening a single aspect in isolation. Given these findings, it is essential to proceed with a sufficiency analysis to explore how different combinations of conditions jointly drive continuous green patent applications in textile firms.

Sufficiency analysis

Unlike necessary condition analysis, causal configuration analysis examines the sufficiency of different combinations of antecedent conditions for the outcome from a set-theoretic perspective. The analysis requires setting frequency and consistency thresholds. The frequency threshold specifies the minimum number of cases per configuration, excluding cases below this value. Following established practices, we set the raw consistency threshold, the proportional reduction in inconsistency (PRI) threshold, and the case frequency threshold to 0.8, 0.7, and 1, respectively. The fsQCA procedure produces three solution types: the complex solution, the intermediate solution, and the parsimonious solution. We primarily report the intermediate solution, using the parsimonious solution to distinguish core conditions within the configurations [36]. Given causal asymmetry, we also report configurations associated with the absence of high continuous green innovation.

Table 2 shows that the four solution configurations for high levels of continuous green patent applications achieve an overall solution consistency of 0.817,

exceeding the minimum threshold of 0.75 [41], with a solution coverage of 0.585. This indicates that these configurations collectively explain approximately 58.5% of the cases, demonstrating improved levels of continuous green patent applications among textile firms. Furthermore, comparing the consistency and raw coverage scores of individual configuration paths (figure 3), L2b exhibits the highest values on both metrics. This suggests that configuration L2b demonstrates the strongest explanatory power for high levels of continuous green patent applications, indicating greater robustness and representativeness.

Table 3 shows that the solution for low levels of continuous green patent applications achieves an overall consistency of 0.813, exceeding the minimum threshold of 0.75, with a solution coverage of 0.602. This accounts for approximately 60.2% of cases exhibiting low levels of continuous green innovation in textile firms. Furthermore, comparison of consistency and raw coverage scores across configuration paths (figure 4) reveals that S4a demonstrates the highest values on both metrics. This indicates that the concurrent absence of executive educational background and government subsidies, when digital transformation is the sole driver, most frequently associates with low levels of continuous green patent applications.

Summary of results

We employ intermediate and parsimonious solutions to identify core and peripheral conditions, categorising them into two archetypes: Environment-Led & Organisation-Coordinated and Technology-Environment-Driven.

1. Environment-Led and Organisation-Coordinated (L1a+L1b)

Configuration L1a exhibits a consistency of 0.838 and raw coverage of 0.340, accounting for approximately 34% of sample cases. Configuration L1b shows a consistency of 0.876 and raw coverage of 0.266, explaining approximately 27% of sample cases. In L1a, firm size, media attention, and government subsidies constitute core conditions, while

Table 2

CONFIGURATION ANALYSIS FOR HIGH LEVELS OF CONTINUOUS GREEN PATENT APPLICATIONS				
Causal conditions	Environment-Dominant-Organizational coordination		Technology-Environment driven	
	L1a	L1b	L2a	L2b
Firm size	☐	☐		★
Digital transformation	★		☐	☐
Executive educational attainment	★	☐	★	★
Media attention	☐	☐	☐	☐
Government subsidies	☐	☐	☐	☐
Consistency	0.838	0.876	0.868	0.895
Raw coverage	0.340	0.266	0.328	0.394
Unique coverage	0.117	0.024	0.008	0.073
Solution consistency	0.817			
Solution coverage	0.585			

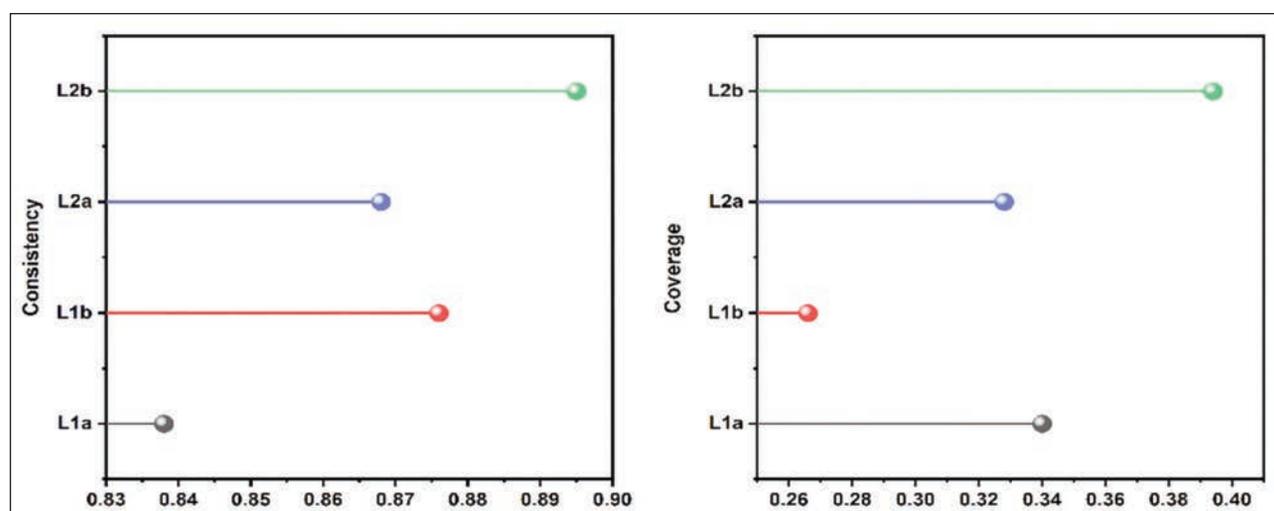


Fig. 3. Consistency and coverage

Table 3

CONFIGURATION ANALYSIS FOR LOW LEVELS OF CONTINUOUS GREEN PATENT APPLICATIONS								
Causal conditions	Environment-Absent		Technology-Deficient			Organizationally Weak	Single-Factor Presence	
	S1a	S1b	S2a	S2b	S2c	S3a	S4a	S4b
Firm size	*		*	*	*	☐		☐
Digital transformation		*	☐	☐	☐		☐	
Executive educational attainment	★	*		★	☐	☐	☐	
Media attention	☐	☐	*	*	★	★	*	☐
Government subsidies	☐	☐	★	*	*		☐	☐
Consistency	0.836	0.897	0.910	0.886	0.834	0.910	0.912	0.855
Raw coverage	0.484	0.243	0.216	0.368	0.334	0.216	0.486	0.244
Unique coverage	0.107	0.015	0.008	0.015	0.012	0.008	0.005	0.014
Solution consistency	0.813							
Solution coverage	0.602							

Note: ☐ denotes the presence of a core condition; ☐ denotes the absence of a core condition; ★ denotes the presence of a peripheral (contributing) condition; * denotes the absence of a peripheral (contributing) condition; "blank" indicates that the condition's presence or absence is irrelevant for the configuration.

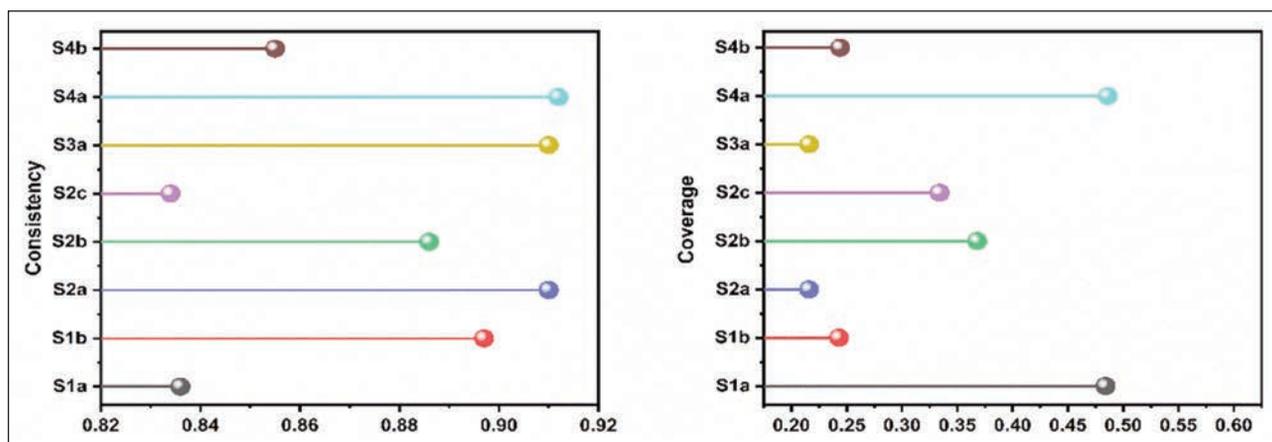


Fig. 4. Consistency and coverage

digital transformation and executives' educational attainment play supplementary roles. This indicates that in the textile industry, firms of substantial scale more readily secure government subsidies and media attention. The continuous infusion of these external resources facilitates green innovation activities. In such cases, while the firm's digital infrastructure and managerial education level are not decisive, they provide effective support in resource utilisation and innovation implementation. In L1b, firm size, executives' educational attainment, media attention, and government subsidies form core conditions, suggesting that large textile enterprises with management teams possessing advanced degrees better identify and respond to external policy and public opinion pressures, thereby enhancing responsiveness to green transformation. This configuration reinforces the synergistic effect between internal organisational capabilities and external drivers. Collectively, the L1a and L1b pathways emphasise macro-level drivers, such as government funding and public oversight, while relying on internal organisational foundations like economies of scale or executive competence. Thus, we designate this archetype as Environment-Led and Organisation-Coordinated.

2. Technology-Environment-Driven (L2a+L2b)

Configuration L2a demonstrates a consistency of 0.868 and raw coverage of 0.328, accounting for approximately 33% of sample cases. Configuration L2b yields a consistency of 0.895 and raw coverage of 0.394, explaining approximately 39% of sample cases. In L2a, digital transformation, media attention, and government subsidies constitute core conditions, with executives' educational attainment playing a supplementary role. This indicates that in advancing green innovation within the textile industry, digital transformation serves as the key driver for optimising resource allocation and upgrading process control, while sustained media attention and government subsidies provide powerful external incentives. Although executive teams with advanced degrees lack decisive influence, they enable more effective policy integration and enhance green strategy implementation efficiency. In L2b, digital transformation, media attention, and government subsidies similarly

form core conditions, with firm size and executives' educational attainment also contributing significantly. This suggests that achieving green innovation in the textile industry requires not only digital capabilities and external support but also adequate resource foundations and managerial competencies, facilitating synergistic improvements in technology absorption, policy alignment, and resource integration during green innovation. Overall, both L2a and L2b pathways underscore the co-driving effects of technological factors and the macro-environment. Therefore, we designate this archetype as Technology-Environment-Driven.

3. We also identified eight configurations leading to low sustained green patent applications in textile enterprises. Based on their distinctive features, we categorise these as: Environment-Absent, Technology-Deficient, Organisation-Weak, and Single-Factor Presence pathways. In configurations S1a, S1b, S2a, S2b, S2c, and S3a, core conditions are consistently absent, demonstrating that enhanced sustained green patent levels in textile firms only occur when coordination exists among micro-, meso-, and macro-level factors. In S4a and S4b, only digital transformation and media attention act independently as core conditions, indicating that achieving sustained green patent applications in this industry emerges not from isolated drivers but from multifactor synergies.

Comparative analysis of configurations generating high versus low sustained green patent applications reveals significant causal asymmetry (figure 5). Specifically, the condition sets enabling high-level outcomes are not merely negations of those producing low-level outcomes. Notably, across all four high-outcome pathways (L1a, L1b, L2a, L2b), media attention and government subsidies consistently appear as core conditions, highlighting their universal applicability in driving high sustained green patent applications.

Robustness analysis

In fsQCA, robustness testing can be performed through multiple approaches, such as adjusting the frequency threshold and consistency threshold to

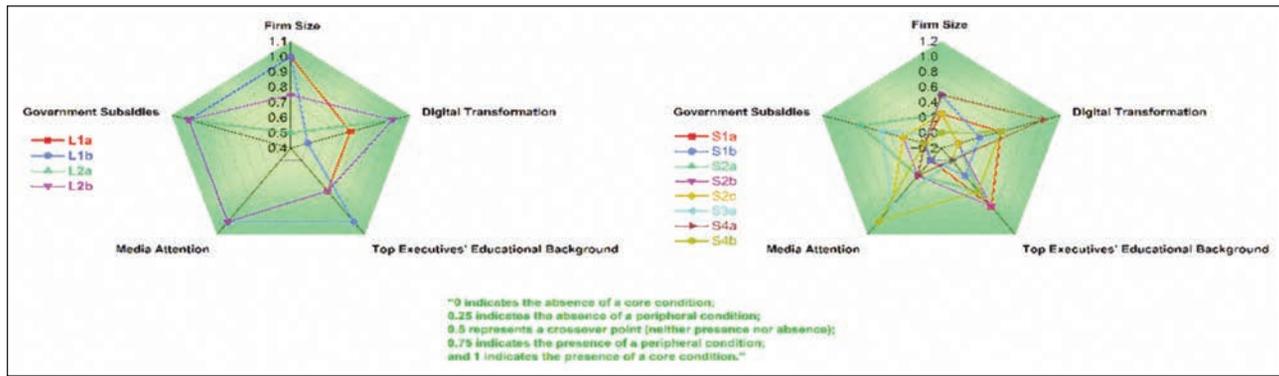


Fig. 5. Configuration radar chart

examine configuration stability under alternative specifications. For this study, we modified the frequency threshold from its original value to 2 while maintaining other parameters, releasing additional

borderline cases and enabling observation of configuration changes. Table 4 shows that core pathways (L1a, L1b, and L2b) persist and closely match original results. These outcomes represent a subset of the high-level configurations in table 2, demonstrating robust stability of key configurations across parameter settings. Table 5 further indicates that pathways generating low-level sustained green patent applications remain essentially unchanged structurally. Collectively, post-adjustment comparative analysis confirms the strong robustness of our identified critical configurations, with research conclusions maintaining high explanatory power and credibility under alternative specifications.

Table 4

HIGH-LEVEL SUSTAINED GREEN PATENT APPLICATIONS (ROBUSTNESS TEST)			
Causal Conditions	L1a	L1b	L2b
Firm size	☐	☐	
Digital transformation	★		☐
Executive educational attainment		☐	★
Media attention	☐	☐	☐
Government subsidies	☐	☐	☐
Consistency	0.838	0.868	0.869
Raw coverage	0.340	0.328	0.356
Unique coverage	0.129	0.049	0.090
Solution consistency	0.824		
Solution coverage	0.563		

Note: ☐ denotes the presence of a core condition; ☐ denotes the absence of a core condition; ★ denotes the presence of a peripheral (contributing) condition; ★ denotes the absence of a peripheral (contributing) condition; "blank" indicates that the condition's presence or absence is irrelevant for the configuration.

CONCLUSION

We selected 48 Chinese A-share listed textile enterprises as our sample. Drawing upon social-ecological system theory, we employed NCA necessity analysis and fsQCA to investigate the mechanisms and pathways influencing enterprises' sustained green patent applications. Our main conclusions are as follows:

(1) Digital transformation, enterprise scale, executive educational background, government subsidies, and media attention are important factors affecting the level of sustained green patent applications in textile

Table 5

LOW-LEVEL SUSTAINED GREEN PATENT APPLICATIONS (ROBUSTNESS TEST)								
Causal conditions	S1a	S1b	S2a	S2b	S2c	S3a	S4a	S4b
Firm size	*	*	*	*	*	☐	*	*
Digital transformation		*	☐	☐	☐	*	☐	*
Executive educational attainment		*		*	☐	☐	☐	*
Media attention	☐	☐		*		★	*	☐
Government subsidies	☐	☐	★		*			☐
Consistency	0.836	0.908	0.929	0.886	0.834	0.910	0.912	0.855
Raw coverage	0.384	0.205	0.335	0.368	0.334	0.216	0.435	0.244
Unique coverage	0.110	0.010	0.018	0.015	0.012	0.008	0.005	0.014
Solution consistency	0.875							
Solution coverage	0.575							

Note: ☐ denotes the presence of a core condition; ☐ denotes the absence of a core condition; ★ denotes the presence of a peripheral (contributing) condition; ★ denotes the absence of a peripheral (contributing) condition; "blank" indicates that the condition's presence or absence is irrelevant for the configuration.

enterprises, and contribute in distinct ways across different configurations. However, NCA results indicate that none of these five factors individually constitutes a necessary condition for enhancing green patent performance. Instead, firms' green patent capability is more dependent on the synergistic configuration and complementary mechanisms of multiple factors.

(2) We identified four configurations that lead to a high level of sustained green patent applications in textile enterprises. These can be categorised into two main pathways: the environment-dominated–organisational collaboration pathway and the technology–environment-driven pathway.

(3) Across all high-level green patent application configurations, media attention and government subsidies consistently appear as core conditions. This demonstrates the universality and criticality of these two macro-environmental factors in promoting green innovation in textile enterprises, highlighting their importance for achieving high-level green patent output.

(4) The conditional configurations affecting green patent applications in textile enterprises exhibit clear causal asymmetry. That is, the combination of factors leading to high-level green patent applications is not equivalent to the inverse configuration of conditions resulting in low-level applications.

This study offers significant theoretical and practical implications. Firstly, it expands the research perspective on sustained green patent applications. While existing literature primarily focuses on the linear effects of single factors [10, 21, 22], our study, grounded in configuration theory, identifies the synergistic mechanisms through which multiple factors drive sustained green patent applications. This actively responds to recent calls for research on the coupling of ecological elements [24, 42]. Secondly, we confirm the asymmetric nature of causality: the combinations of conditions leading to high-level innovation cannot simply be inverted to explain low-level innovation. This finding enriches the theoretical understanding within the green innovation domain.

Based on our findings, we propose the following policy implications to effectively enhance continuous green innovation in textile firms:

- First, from the perspective of textile firm managers, achieving high-level continuous green innovation requires a holistic approach. Managers must consider the intricate interplay among micro, meso, and macro-level factors rather than focusing on a single dimension. By adopting a configurational

mindset, they can make informed decisions that promote sustained green innovation. For instance, along the environment-led and organisational synergy path, managers should strengthen communication with government bodies and media outlets, actively seek subsidies and public support, and leverage their firm's size to establish cross-departmental coordination. This will enhance their responsiveness to external changes and avoid the risk of low innovation levels, a finding consistent with our conclusion that no single factor is a necessary condition for green innovation.

- Second, government departments should pay greater attention to the incentive role of environmental subsidies in promoting green technology innovation within the textile industry and improve the precision and alignment of policy design. For firms on the environment-led and organisational synergy path, the focus should be on refining the mechanisms for precise subsidy allocation and oversight to ensure funds are used for optimising green production processes and building organisational capabilities. For firms on the technology–environment driven path, increased financial and tax support should be directed toward R&D and digital transformation projects. This targeted support can more effectively stimulate green innovation and facilitate the sustainable development of the textile industry by matching policy design with the specific characteristics of each pathway.

Our use of the fsQCA method to identify sufficient condition combinations is intended to complement, not replace, traditional regression analysis that uncovers the net effects of single variables. This approach provides a richer perspective on complex causal relationships. Despite our contributions, this study has several limitations. First, our reliance on cross-sectional data for static analysis limits our ability to capture temporal dynamics. Future research could apply time-series or dynamic QCA methods to explore the long-term effects of antecedent variables on continuous green innovation. Second, while we selected a comprehensive set of empirically tested variables from existing literature across micro, meso, and macro levels, we may have omitted some key factors due to data availability and sample characteristics. The complexity of firms' motivations for continuous green innovation may not be fully captured. Future studies could expand the variable dimensions to include factors like corporate culture or governance structures.

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