

Article

The Synergistic Empowerment of Digital Transformation and ESG on Enterprise Green Innovation

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Abstract

Digital transformation enhances the processes and efficiency of enterprise green innovation through technological empowerment, while the ESG framework guides the direction and value of such innovation via institutional norms. However, existing studies often examine digital transformation and ESG in isolation, resulting in insufficient exploration of their synergistic effects. Based on data from manufacturing high-tech enterprises, this study employs necessary condition analysis (NCA) and fuzzy-set qualitative comparative analysis (FsQCA) to systematically examine the synergistic effects of digital transformation and ESG on enterprise green innovation. The key findings are as follows: (1) While no single factor constitutes a necessary condition for high green innovation, the elements of social governance and digital management demonstrate universal applicability in enabling enterprises to achieve high levels of green innovation. (2) The dual-core-driven configuration achieves green innovation through the synergy between social governance and digital management, with its specific pathways varying according to the coordinated combinations of auxiliary factors. This delineates three distinct types, including compliance-oriented, environmentally empowered, and comprehensively balanced pathways. (3) The digitally driven configuration establishes an endogenous linkage between technological innovation and green development through the deep coupling of digital technology R&D and application. (4) The low green innovation configuration exhibits insufficient efficacy due to either isolated single elements or the absence of digital management, resulting in suboptimal green innovation performance. This study empirically demonstrates that the effective advancement of green innovation fundamentally relies on the endogenous dynamics of social governance, the technological underpinnings of digital management, and the systemic synergy among key elements, offering significant strategic implications for enterprises to develop differentiated green innovation approaches.

Keywords: digital transformation; ESG; green innovation; synergistic empowerment; high-tech enterprises



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1. Introduction

Against the backdrop of intensifying global climate change and ecological environmental challenges, the enterprise adoption of green innovation strategies has emerged as a critical breakthrough for advancing sustainable economic development [1,2]. With the fast rise in the digital economy, digital transformation and environmental, social, and governance (ESG) practices are now widely seen as two key strategies. More and more companies are using them to boost green innovation. Digital transformation uses advanced

technologies to improve how accurately resources are allocated and how efficiently operations are run [3]. This helps greatly in cutting energy use and pollution during production. At the same time, the ESG framework helps companies build a full environmental management system. It builds environmental performance metrics directly into strategic planning, making sustainability a regular part of business practice.

Digital transformation serves as a pivotal driver of enterprise green innovation by establishing a robust technological support system [4]. This system significantly enhances both the intelligence and efficiency of resource allocation [5], while enabling systematic integration of internal and external R&D resources. Emerging digital technologies not only optimize innovation systems through improved element coordination [3], but also dismantle information barriers inherent in traditional innovation processes. These technologies establish real-time connections between environmental monitoring data and innovation decision-making [6]. Enterprises can leverage robust data mining and analytical capabilities to accurately identify evolving market trends and shifting consumer demands [7]. This capability drives sustainable business models [8] and enables a dynamic closed-loop value system [9,10], significantly advancing both the precision and efficiency of green innovation in enterprises.

The ESG framework serves as a critical mechanism for advancing enterprise sustainable development by establishing a tripartite evaluation system integrating environmental responsibility, social responsibility, and enterprise governance. This integrated indicator system has gained widespread international recognition as the paramount standard for assessing green development performance [11,12], while facilitating structural optimization and upgrading in capital market investments [13]. It can motivate enterprises to implement green innovation initiatives. By enhancing ESG performance, enterprises can convey positive signals to capital markets regarding their active fulfillment of social responsibilities and emphasis on environmental management. This information disclosure mechanism significantly mitigates market information asymmetry caused by inefficient communication channels [14]. Such enhanced transparency helps strengthen investor confidence in companies' long-term value growth potential, encouraging increased financial support for green technology innovation projects [15,16]. This virtuous-cycle mechanism will ultimately significantly enhance enterprises' intrinsic motivation to engage in green innovation activities and propel their overall green innovation capabilities to achieve substantial leaps [17].

In current enterprise practice, the synergistic development of digital transformation and ESG faces significant fragmentation challenges. Some companies rely too much on digital tools to solve environmental problems. They use technology without following ESG strategic guidance. Other businesses focus only on ESG rules but do not use digital technology effectively. This keeps their environmental efforts shallow. Both approaches limit green innovation success. Without ESG guidance, digital tools are not used to their full potential. Without digital support, ESG goals are hard to achieve in practice. Therefore, it is important to study how digital transformation and ESG can work together. However, existing research has not yet delved into how digital transformation and ESG work together. More importantly, it is still unknown whether the collaborative configuration between digital transformation and ESG can achieve high levels of green innovation development. Based on this, this study will delve into the collaborative configuration of digital transformation and ESG on enterprise green innovation, to find a pathway for high levels of green innovation development.

This study makes the following contributions: (1) From the perspective of institutional theory, to obtain the legitimacy recognition of the government and the market, enterprises need to attach importance to the coordinated development of digital transformation and ESG practices. At present, most research on green innovation only explores this issue

from the perspective of digital transformation [4] or ESG practices [17]. However, in real life, the factors that affect green innovation do not exist in isolation. This article will analyze how listed companies can promote the implementation of green innovation under the guidance of legitimacy. (2) This article expands on existing green innovation research methods. This study employs the fuzzy-set qualitative comparative analysis (FsQCA) approach to systematically investigate the multidimensional synergistic effects between ESG practices and digital transformation. Compared with the inherent linear assumption limitations of traditional regression analysis, this method precisely captures the complex combinatorial effects of multiple antecedent conditions, providing a novel analytical perspective and research paradigm for understanding heterogeneous pathways in enterprise green innovation implementation.

The paper is structured as follows: Chapter 2 elaborates the theoretical basis and literature review; Chapter 3 presents the methodology, including data sources, research method, variables, and its calibration; Chapter 4 reports the result analysis, comprising necessary condition analysis (NCA), necessity analysis, configuration analysis, and robustness test. Finally, the research conclusion and discussion are presented. Additionally, Figure 1 comprehensively illustrates the research framework of this study.

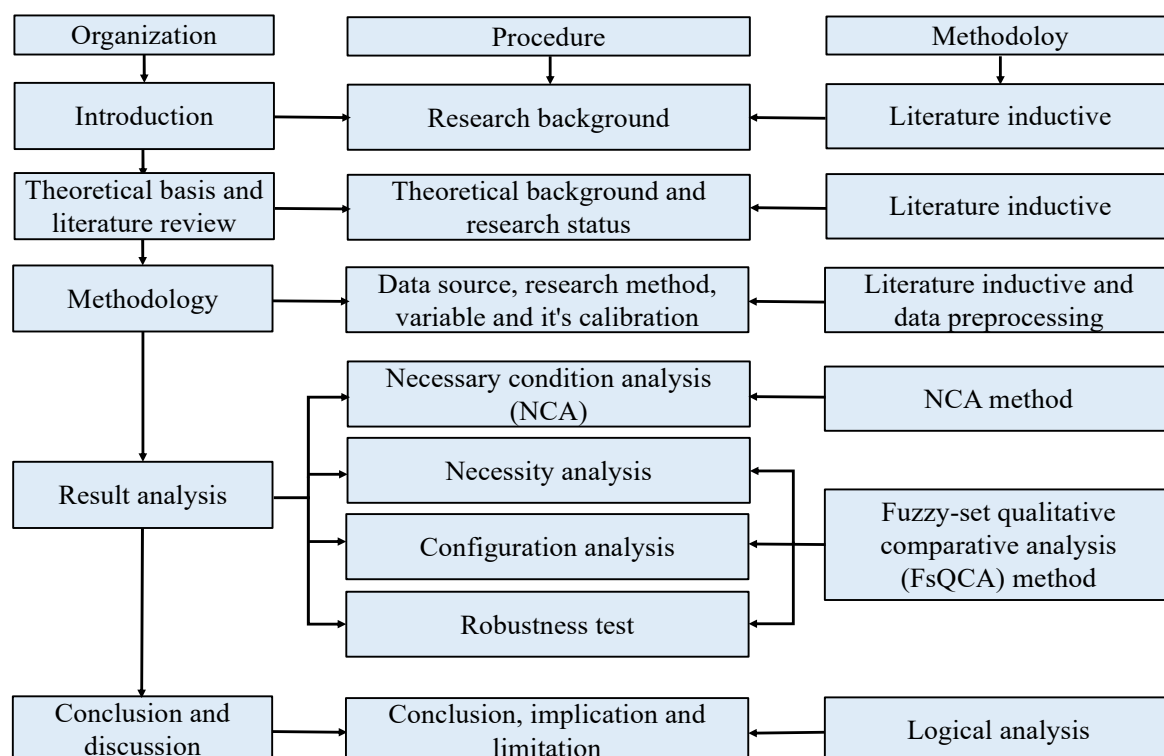


Figure 1. The research framework.

2. Theoretical Basis and Literature Review

2.1. Theoretical Basis

As companies interact with their environment, they also face diverse external conditions, creating institutional complexity [18]. This complexity arises from multiple institutional logics within their environment. In such multi-logic systems, each institutional order operates under its own logic, while firms also respond to these varied external pressures [19]. To gain legitimacy, companies adhere to institutional rules and conditions, which exert implicit pressure on corporate behavior [20,21]. It also can provide sustained competitive advantage for enterprises [22] and promote green development [23].

Existing literature indicates that ESG practices result from the coupling and interaction of multiple actors, including governments, markets, and corporations, working together to drive outcomes [24]. ESG aims to meet stakeholders' expectations in exchange for more resources and support to ensure survival and growth. Thus, corporate ESG investment is a response to government regulations and market conditions, seeking to gain "legitimacy" and favorable development conditions [25]. Moreover, the pursuit of legitimacy also motivates companies to implement digital transformation [26]. Institutional pressure compels firms to acquire and reconfigure internal and external resources to enhance their digital capabilities and gain external recognition [27]. When the difficulty and benefits of digital transformation are hard to assess, companies often imitate recognized competitors within the industry by adopting similar practices in response to strategic challenges [28,29].

In summary, the synergy between digital transformation and ESG plays a crucial role in strengthening corporate legitimacy. On one hand, ESG practices represent a strategic response to government policies, market mechanisms, and stakeholder expectations, aimed at gaining legitimacy and development resources by complying with external requirements [25]. Digital transformation enhances a company's credibility in regulatory compliance and market competition, enabling it to respond more effectively to institutional pressures. On the other hand, digital transformation itself is driven by the pursuit of legitimacy. Under cognitive pressure, companies learn from the digital practices of legitimate industry leaders to reduce trial costs and gain external recognition faster amid uncertainty and technological ambiguity [30]. The ESG framework provides digital transformation with clear strategic direction and practical application scenarios, ensuring alignment with sustainable development goals. Together, they help firms build enduring legitimacy, attract resources, and achieve long-term growth.

2.2. The Impact of ESG on Enterprise Green Innovation

Green innovation practices encounter significant implementation barriers due to their inherent high-risk nature and output uncertainty, compounded by dual constraints of regulatory gaps and limited factor inputs [31]. Against this backdrop, the ESG performance evaluation mechanism provides an innovative solution to overcome this development bottleneck [32,33]. It not only contributes to optimizing enterprise internal governance structures [34] but also significantly enhances market valuation [35], demonstrating substantial positive effects on promoting green innovation development [36,37]. Specifically:

In terms of financing constraints, superior ESG performance provides critical financial support for green innovation by effectively mitigating enterprise external financing limitations [38,39]. As a non-financial evaluation framework for assessing enterprise sustainable development capabilities [40], the ESG disclosure mechanism significantly enhances information transparency between enterprises and capital providers, enabling investors to more comprehensively identify and evaluate the long-term value of green innovation projects. The optimized information environment effectively mitigates financing constraints for innovative enterprises [41,42], diversifies financing channels [43], and crucially resolves funding shortages for traditional heavy-polluting firms confronting energy transition challenges [16]. Research demonstrates that superior ESG performance significantly reduces enterprise debt financing costs and equity capital costs [44], thereby establishing a stable funding system for sustained green R&D activities. More importantly, ESG practices cultivate an environmentally responsible enterprise image [45], substantially enhancing trust among stakeholders including investors, suppliers, and clients. This accumulation of intangible reputation capital not only facilitates the attraction of strategic capital with long-term value investment perspectives, but also promotes deep collaborative innovation

in green technology development across industrial chain segments, ultimately forming a virtuous-cycle green innovation ecosystem.

In terms of supervisory governance, the ESG performance evaluation mechanism exerts significant positive impacts on enterprise green innovation activities by enhancing the completeness and reliability of enterprise information disclosure [46]. As a comprehensive evaluation standard for enterprise non-financial performance, the ESG rating framework effectively bridges the information gap between enterprises and their stakeholders [14], enabling various interest groups to assess enterprise environmental protection and social responsibility performance more systematically and accurately. This external supervisory governance mechanism not only significantly enhances operational transparency [47], but also effectively curbs potential opportunistic behaviors [48]. Under increasingly stringent external oversight, enterprise management decision-makers are compelled to integrate environmental performance and social responsibility into strategic considerations, thereby proactively increasing resource allocation for green technology R&D and clean production innovation [49–51]. Moreover, the standardization process of ESG disclosure inherently fosters enterprise environmental responsibility culture [52,53], prompting enterprises to prioritize sustainable development objectives when formulating long-term strategies, ultimately guiding them toward adopting more environmentally friendly production models and technological innovation pathways.

2.3. The Impact of Digital Transformation on Enterprise Green Innovation

Currently, enterprise digital transformation has evolved from the initial stage of technological tool application to a strategic-level systemic change, making it a key driver for comprehensive organizational innovation and value system restructuring [54]. Research on digital transformation encompasses not only adoption mechanisms and application pathways of digital technologies [55], but also delves into how these technologies fundamentally reshape enterprise strategic decision-making models and business management paradigms [56]. Relevant studies demonstrate that digital transformation fundamentally alters the intrinsic logic of enterprise value creation [57], thereby opening new strategic pathways for organizations to build sustainable competitive advantages in the digital economy era [3,58]. Also, existing research confirms that implementing digital transformation strategies can effectively drive the enhancement of enterprise green innovation performance [59,60]. Specifically:

From a technological perspective, the continuous evolution and deep penetration of digital technologies have significantly enhanced enterprise information processing and analytical capabilities, which establishes a solid technical foundation for intelligent restructuring of organizational processes and green transformation of production models [61,62]. Specifically, intelligent technology can help companies collect and intelligently analyze carbon emission data in real-time, thereby significantly optimizing the efficiency of green resource allocation [63,64]. The deep integration and application of artificial intelligence technologies in critical areas optimization not only significantly enhance work efficiency, but also substantially reduce resource waste and trial-and-error costs during development [65]. This systematic digital transformation synergistically improves enterprise innovation efficacy and environmental-economic performance [66].

From a management perspective, digital transformation shifts enterprise management models from traditional experience-driven approaches to data-driven intelligent paradigms [67]. This transition enables enterprises to respond more agilely to market dynamics and environmental policy adjustments. Furthermore, digital transformation profoundly reshapes enterprise knowledge management architectures [68] and innovation

resource integration mechanisms [69,70], establishing comprehensive institutional frameworks and resource guarantee systems for the sustained advancement of green innovation.

At the practical application level, digital transformation demonstrates effects including reduced information acquisition costs [71], enhanced information symmetry [15], and optimized resource allocation paradigms [67]. During this process, the intelligent mining and integrated application of both structured and unstructured data play a pivotal role. By leveraging advanced algorithms such as machine learning, enterprises can extract commercially valuable insights from complex unstructured text data. Furthermore, through cross-validation and comprehensive analysis with structured data, they achieve precise market demand forecasting. This data-driven innovation model not only significantly enhances enterprise market responsiveness [72], but also promotes collaborative innovation and green development across industrial chain ecosystems.

3. Methodology

3.1. Data Source

This study selects China's listed manufacturing high-tech enterprises in 2021 as research subjects because this sector uniquely combines high environmental sensitivity and urgent digital transformation needs. Firstly, manufacturing high-tech enterprises face particularly prominent issues of energy consumption and pollution emissions due to their production processes, thus requiring ESG implementation to advance sustainable development. Secondly, to enhance production efficiency and achieve low-carbon manufacturing, these enterprises actively adopt digital technologies such as Industrial Internet and artificial intelligence. Selecting these enterprises as research subjects precisely aligns with the study's thematic requirements. The data, sourced from the CSMAR database, Wind database, and China's National Intellectual Property Administration, yielded valid datasets for 296 enterprises after excluding samples with missing key variables.

3.2. Research Method

This study employs the FsQCA method to thoroughly investigate the multiple path configurations through which ESG practices and digital transformation synergistically promote enterprise green innovation. This research methodology is grounded in the fundamental principles of Boolean algebra and set theory [73], making it particularly suitable for analyzing complex interaction effects among multiple antecedent conditions and their synergistic mechanisms on outcome variables [74]. The specific formulas are as follows:

$$\mu X_i = \frac{1}{1 + e^{-a(x_i - b)}} \quad (1)$$

$$\text{Consistency} = \frac{[\min(\mu X_i, \mu Y)]}{\mu X_i} \quad (2)$$

$$\text{Coverage} = \frac{[\min(\mu X_i * \mu X_j, \mu Y)]}{\mu Y}, i \neq j \quad (3)$$

where Consistency denotes consistency, Coverage represents coverage, a determines the slope, and b indicates the crossover point.

3.3. Research Variable

This study focuses on examining how ESG and digital transformation synergistically empower enterprise green innovation, primarily involving three core variables: ESG, digital transformation, and enterprise green innovation.

ESG, as a comprehensive enterprise evaluation framework and investment strategy, fundamentally involves systematically assessing enterprise performance across three core dimensions: environmental practices (X1), social practices (X2), and governance practices (X3) [32,33]. This evaluation framework not only provides investors with non-financial performance assessment criteria but also promotes enterprise adoption of sustainable development principles and strengthens social responsibility awareness through its multi-dimensional assessment mechanism. Following prevailing research practices, We adopt the ESG rating results from the Shanghai Stock Exchange (SSE) Index as the research variable.

Enterprise digital transformation, as a pivotal driver of contemporary organizational change, comprehensively empowers innovation activities and provides solid technological foundations with systematic support conditions for green innovation implementation. Drawing on existing research ideas [75], this study conceptualizes enterprise digital transformation through three key dimensions, including digital R&D (X4), digital management (X5), and digital application (X6). Specifically, we extract and statistically analyze keyword frequencies related to digital transformation from the “Management Discussion and Analysis” (MD&A) sections of annual reports of listed companies in the CSMAR database, employing text mining techniques aligned with the three dimensions [76].

Enterprise green innovation (Y), as a critical component of sustainable development strategies, is conventionally defined as a technological innovation process wherein enterprises conduct environmentally friendly R&D activities. It aims to promote ecological conservation and sustainable resource utilization, thereby significantly reducing energy intensity, effectively controlling pollution emissions, or continuously optimizing eco-economic efficiency [51]. In line with prevailing academic measurement paradigms [77], this study selects the annual count of green technology invention patent applications as the metric.

The logical framework of this article is shown in Figure 2.

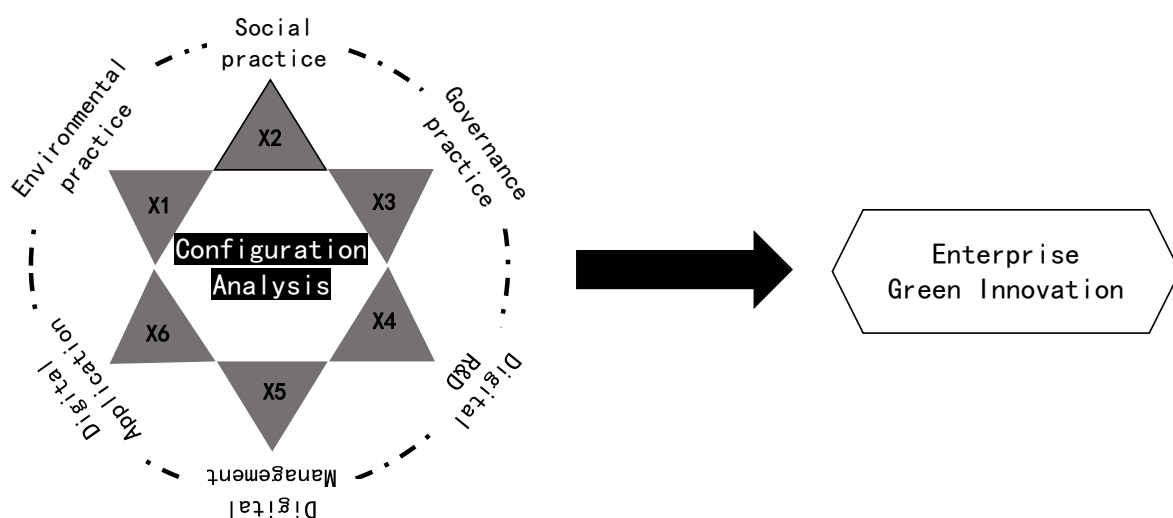


Figure 2. The logical framework.

3.4. Variable Calibration

This study employs direct calibration techniques to transform raw observed values into fuzzy-set membership scores, utilizing 0.90 (full membership), 0.50 (crossover point between membership and non-membership), and 0.10 (full non-membership) as calibration anchors. Since the software automatically excludes samples with membership scores equal to 0.5 during data processing, this study implements necessary technical adjustments by re-calibrating borderline cases from 0.500 to 0.501 to ensure sample integrity and analytical reliability [78]. This ensures all eligible observational data can fully participate

in subsequent configuration path analysis. The results of variable calibration are shown in Table 1.

Table 1. Variable calibration.

Variable	Anchor Point		
	Full Membership	Crossover Point	Full Non-Membership
X1	4.03	0.60	0.00
X2	4.13	1.50	0.00
X3	3.90	2.43	0.00
X4	46.00	6.00	0.00
X5	15.00	1.00	0.00
X6	38.00	7.00	0.00
Y	31.00	2.00	0.00

4. Result Analysis

4.1. Necessary Condition Analysis

This study employs NCA to examine the necessity of potential antecedent variables, with the judgment primarily relying on effect size and bottleneck thresholds. Specifically, the effect size quantifies the constraining degree of antecedent variables on the outcome variable, while the bottleneck threshold is defined as the minimum requirement level that antecedent variables must meet for the outcome variable to achieve optimal performance. Based on the measurement characteristics of variables, this study adopts both ceiling regression (CR) and ceiling envelopment (CE) estimation methods, which are, respectively, applicable to the analysis requirements of continuous and discrete variables [79].

Table 2 presents the necessary condition analysis results, indicating that none of the examined antecedent variables meet the judgment criteria for being necessary conditions of enterprise green innovation.

Table 2. Results of necessary condition for NCA method.

Y	X1	X2	X3	X4	X5	X6
0	NN	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN	NN
30	NN	NN	NN	NN	NN	NN
40	NN	NN	NN	NN	NN	NN
50	NN	NN	NN	NN	NN	NN
60	NN	NN	NN	NN	NN	NN
70	NN	NN	NN	NN	NN	NN
80	NN	NN	NN	NN	NN	NN
90	NN	NN	NN	NN	NN	2.1
100	NN	NN	NN	5.3	NN	4.1

Note: (1) The method refers to CE. (2) “NN” denotes “not necessary”.

The analysis results in Table 3 demonstrate that antecedent variables exhibit significant standard requirement when enterprise green innovation performance reaches its optimal level. The digital R&D dimension requires achieving 5.3% of its observed value range, while the digital application dimension needs to reach a 4.1% minimum threshold. Other examined variables demonstrate no statistically significant bottleneck level characteristics. This finding further validates the aforementioned conclusion that none of the antecedent variables meet the judgment criteria as necessary conditions for enterprise green innovation.

Table 3. Results of bottleneck level for NCA method.

Variable	Method	Accuracy%	Interval	Range	d	p Value
X1	CR	100.00	0.00	0.90	0.00	1.00
	CE	100.00	0.00	0.90	0.00	1.00
X2	CR	100.00	0.00	0.90	0.00	1.00
	CE	100.00	0.00	0.90	0.00	1.00
X3	CR	100.00	0.00	0.90	0.00	1.00
	CE	100.00	0.00	0.90	0.00	1.00
X4	CR	100.00	0.00	0.90	0.00	1.00
	CE	100.00	0.00	0.90	0.00	1.00
X5	CR	100.00	0.00	0.90	0.00	1.00
	CE	100.00	0.00	0.90	0.00	1.00
X6	CR	100.00	0.00	0.90	0.00	1.00
	CE	100.00	0.00	0.90	0.00	1.00

Note: (1) Effect sizes in range $0 \leq d < 0.1$ indicate low-level necessity. (2) Permutation test in NCA employed 10,000 resampling iterations.

4.2. Necessary Analysis

To comprehensively verify the necessity characteristics of antecedent conditions, this study conducts supplementary tests using the FsQCA method. A variable can only be recognized as a necessary condition for the outcome when its consistency coefficient surpasses the critical threshold of 0.9. The results in Table 4 demonstrate that none of the variables' consistency indices meet this judgment criterion (0.9), indicating significant limitations in the explanatory power of individual factors regarding enterprise green innovation. This finding significantly corroborates the earlier NCA findings, demonstrating that enterprise green innovation stems from multi-factorial synergistic effects rather than depending on isolated necessary conditions.

Table 4. Results of necessary condition for FsQCA method.

	Y		~Y	
	Consistency	Coverage	Consistency	Coverage
X1	0.601979	0.6408	0.489031	0.59629
~X1	0.620748	0.514699	0.705411	0.669977
X2	0.624035	0.645002	0.508031	0.60148
~X2	0.614435	0.521607	0.700156	0.680836
X3	0.621257	0.618251	0.541866	0.617683
~X3	0.615824	0.539914	0.665108	0.667943
X4	0.586991	0.611572	0.551582	0.658272
~X4	0.672007	0.566783	0.674527	0.651661
X5	0.595156	0.631835	0.519525	0.63177
~X5	0.653146	0.542701	0.697246	0.663615
X6	0.617414	0.607392	0.586225	0.660598
~X6	0.654998	0.580179	0.651592	0.661116

Note: ~ denotes negation in fuzzy-set theory.

4.3. Configuration Analysis

This study establishes the case frequency threshold at 1, sets the raw consistency threshold at 0.80, and configures the PRI consistency at 0.60. As presented in Table 5, the analysis identifies four significant configuration paths for achieving enterprise green innovation. These solution configurations demonstrate an overall consistency level of 0.89 and coverage of 0.33, both exceeding the critical thresholds, thereby confirming the reliability and validity of the research findings. The unique coverage measures the proportion explained solely by one solution excluding memberships that are covered by other

solutions [80]. As the unique coverage of each configuration exceeds the value of zero, this complex solution contributes to explaining the outcome (otherwise it should be eliminated).

Table 5. Results of configuration analysis for FsQCA method.

Variable	High Level of Green Innovation				Low Level of Green Innovation	
	S1	S2	S3	S4	NS1	NS2
X1	●	●	●		X	X
X2	●	●	●	●	X	X
X3	●		●	X	X	X
X4		X	X	●	●	X
X5	●	●	●	●	X	X
X6	X	X		●	X	●
Consistency	0.91	0.91	0.88	0.93	0.88	0.87
Raw coverage	0.25	0.22	0.24	0.21	0.19	0.20
Unique coverage	0.02	0.01	0.02	0.05	0.05	0.06
Solution consistency		0.89			0.88	
Solution coverage		0.33			0.25	

Note: ● is a core condition that exists. ● is an auxiliary condition that exists. X indicates that the core condition does not exist. Blank indicates that the condition may or may not exist.

4.3.1. The Comprehensive Analysis of High Green Innovation Level

Although none of the six antecedent elements constitute individual necessary conditions, both social governance and digital management demonstrate universal explanatory power for enterprises to achieve high green innovation. From the social governance perspective, enterprises proactively advance green innovation practices driven by institutional legitimacy demands for strengthened market recognition. They actively respond to societal expectations through product greening transformation and production process innovation, thereby elevating green innovation level. From the perspective of digital management, the rapid growth of the digital economy creates an internal demand for corporate digital transformation. Based on cognitive legitimacy, companies learn from peers that digital management methods can improve operational efficiency and drive green innovation development. In summary, enterprises have strengthened social governance and digital management by meeting market and cognitive legitimacy requirements, promoting the coordinated development of institutional homogeneity and technological innovation in the process of green innovation.

4.3.2. The Grouping Analysis of High Green Innovation Level

(1) The dual-core-driven configuration

Most companies in this group focus mainly on management rather than R&D, or technology applications. These firms improve efficiency by digitizing basic tasks, such as using online platforms and streamlining workflows, while also promoting green innovation through digital patent management and eco-friendly practices. This approach can be divided into three subtypes, differing mainly in how supporting factors are combined to adapt to different situations under the same core strategy. The specific types are as follows:

The compliance-oriented configuration (S1) has social governance and digital management as its core conditions, with enterprise governance acting as a supporting factor. Their key difference being how they implement green innovation through improved governance structures. Most of these companies are in traditional heavy machinery manufacturing, where markets are mature and production technologies are standardized. Their digital

efforts mainly target management rather than R&D, due to the difficulty of digitizing core manufacturing processes. This shows that these firms should focus on adaptive legitimacy demands for green innovation, using better governance to meet energy-saving and emission-cutting goals. This approach makes enterprise governance a secondary but still important factor.

The environmentally empowered configuration (S2) uses social governance and digital management as core elements. These companies show strong environmental awareness to gain market legitimacy. Their production operations are much more closely connected to ecosystems than industry averages. Most of these firms operate in environmentally sensitive industries, including chemicals, steel, and non-ferrous metal smelting. Due to their sectors, they face stricter government regulations. They also receive more public scrutiny than other industries. This shows that dual pressures effectively drive their green innovation practices.

The comprehensively balanced configuration (S3) has social governance and digital management as its core conditions, with environmental and enterprise governance as supporting factors. This type of company gains government and market legitimacy by combining corporate social responsibility, stronger environmental protection, and improved governance structures. They also use digital systems to boost efficiency, balancing management performance with social and environmental goals. Most of these firms operate in consumer goods manufacturing. Since this industry serves end-users, companies prioritize brand image and meet public environmental expectations through ESG practices. Although these manufacturers have limited digital technology capabilities, they fully perceive institutional pressures and establish a governance system based on digital management as the technological foundation, social governance as the main body, and environmental and corporate governance as the support. This will help them gain institutional legitimacy.

(2) The digitally driven configuration

The digitally driven configuration (S4) has four core elements: social governance, digital R&D, digital management, and digital application. Companies in this group feel significant cognitive pressure and focus on pursuing digital technology skills. On the one hand, mature digital tech firms focus on creating digital products and technologies. They use their digital innovation strengths to push tech applications forward. On the other hand, other high-tech firms going through digital change fully restructure their production systems by blending digital tech with their traditional strengths. Although these two kinds of companies started digital transformation at different times, they work in similar ways. Both have built connected systems that combine tech innovation with green development through close teamwork between digital R&D and application. They also use social governance structures and digital management tools to regularly support green innovation.

4.3.3. The Analysis of Low Green Innovation Level

Due to their inability to effectively perceive institutional pressures, firms with low green innovation performance typically rely on just one core element, like digital R&D or digital application alone. This limits their ability to effectively support green innovation. Companies in the R&D-isolated setup (NS1) have digital R&D skills. As a result, their research has little effect on actual green innovation. Those with application-isolated setups (NS2) show weak digital transformation impact. Their use of digital tools stays shallow because they lack strong R&D and digital management. This also keeps them from driving green innovation well. Both types fail to build connections between different stages of digital transformation, which holds back their green innovation development. Furthermore,

both configurations lack the digital management, preventing enterprises from effectively integrating digital competencies with organizational operating systems.

4.4. Robustness Test

If the core configurations obtained through FsQCA method with different parameter settings demonstrate clear inclusion relationships with the original results, this indicates robust research findings [81]. Specifically, this study increased the case frequency threshold from 1 to 2 while elevating the consistency threshold from 0.8 to 0.9. The analysis with adjusted parameters demonstrates that the core configuration indicators remain consistent with the original results, thereby confirming the robustness of the results.

5. Conclusions and Discussion

This study systematically uncovers differentiated pathways for enterprise green innovation from a configurational perspective. The findings reveal the following information: (1) A single factor cannot constitute the necessary condition for green innovation, but a high green innovation level relies on synergistic mechanisms between social governance and digital management. This indicates that green innovation requires the obtention of market legitimacy through social governance and cognitive legitimacy through the use of digital management to alleviate institutional pressures brought about by the external environment. On the one hand, enterprises stimulate innovation willingness by strengthening market recognition through social governance. Further, enterprises can improve process optimization and decision support through digital management, surpassing peer enterprises to gain long-term benefits. (2) The dual-core-driven grouping is primarily applicable to high-tech enterprises with relatively low levels of digital maturity. The specific pathways vary depending on the legality requirements and are divided into three subtypes: compliance-oriented configuration (S1), environmentally empowered configuration (S2), and comprehensively balanced configuration (S3). Among these, the S1 configuration strengthens its internal governance structure through cognitive pressure from peer enterprises. The S2 configuration emphasizes obtaining government legitimacy, thus requiring the auxiliary role of environmental governance. The S3 configuration requires us to integrate social, corporate, and environmental dimensions in order to gain legitimacy from both the government, market and peer enterprises. (3) The digitally driven configuration (S4) deeply reflects the cognitive pressure brought by peer enterprises, thus focusing on pursuing digital transformation. The companies in this group achieve the profound integration of digital technologies with social governance, encompassing both established digital enterprises specializing in digital R&D, and firms undergoing transformation through digital application. (4) The crux of the low level of green innovation lies in the failure to effectively align ESG practices with digital transformation. Although some green innovation results have been achieved by unilaterally pursuing digital transformation, the lack of government and market legitimacy hinders their progress towards higher levels of green innovation.

This study introduces an institutional theory perspective to explain the synergistic effect of ESG and digital transformation on green innovation, offering theoretical implications for related research. Specifically, ESG practices emerge through the joint participation and interaction of multiple actors, including government agencies, markets, and industry peers. Their environmental governance can gain governmental legitimacy and qualify for policy support. Social governance can achieve market legitimacy and enhance competitive advantage. Corporate governance can obtain cognitive legitimacy and alleviate pressure from industry peers. Moreover, digital transformation is driven by competitive pressure from industry peers, which indirectly increases the need for cognitive legitimacy. In this complex

external environment, enterprises should respond to these different external pressures to gain legitimacy.

The practical implications of this study are as follows: (1) All companies should move beyond single-factor innovation models. They need to use digital management as a central hub and deeply integrate social governance into green innovation systems. (2) Traditional heavy machinery high-tech firms must overcome technical limits in core production digitization by improving their governance structures. (3) Chemical high-tech companies should turn environmental rules into drivers for green innovation through active environmental governance. (4) Consumer goods' high-tech manufacturers need to combine operational efficiency, environmental protection, and social responsibility. They can achieve green innovation by integrating technology upgrades, sustainable production, and stakeholder needs. (5) Digital high-tech firms should use a collaborative system covering R&D, management, and application. It helps to turn digital advances into green innovation advantages.

This study has several limitations that warrant further investigation. Firstly, it relies solely on patents as a measure of green innovation. In the future, we should use text analysis to distinguish between green innovation processes, green services, and green management. Secondly, more precise dictionaries for text mining are needed to accurately assess digital transformation and avoid measurement bias. Finally, the use of cross-sectional data limits causal inference, and future research should adopt a wider sample size combined with causal inference algorithms.

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