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The Impact of ESG on Green Innovation: The Mediating Roles of Digitalization and Information Disclosure

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ABSTRACT

This study examines how ESG performance influences green innovation, focusing on its underlying mechanisms and heterogeneous effects across firms and regions. Using panel data for Chinese A-share listed companies from 2009 to 2023, we employ a two-way fixed effects model and use ESG fund exposure as an instrumental variable to support causal identification. Digital transformation and information disclosure quality are incorporated as mediating factors. The results show that ESG performance significantly enhances green innovation, partly through improvements in digital capabilities and information transparency. These findings are robust to alternative specifications and instrumental variable estimations. The positive effects are more pronounced for high-quality innovation, large firms, state-owned enterprises, firms in the decline stage, and those operating in high-pollution, less competitive, and non-digital industries, particularly in eastern regions. Overall, this study advances understanding of how ESG engagement promotes sustainability-oriented transformation and provides important implications for firms and policymakers.

1 | Introduction

Green innovation has become a central corporate response to environmental regulation, resource constraints, and climate risks (Ambec et al. 2013). It reflects firms' ability to develop sustainability-oriented technologies and serves as an important channel for achieving green competitive advantages. While green innovation encompasses multiple dimensions, including organizational and process changes, this study focuses on its technological dimension, which can be systematically measured using green patent applications. Patent-based indicators provide standardized, comparable, and widely accepted measures of firms' environmentally oriented technological activities and

are widely adopted in firm-level empirical research (Hašičič and Migotto 2015; León et al. 2017).

At the same time, environmental, social, and governance (ESG) performance has evolved from a capital market concept into a core element of corporate strategy, shaping firms' long-term value and sustainability orientation (Weston and Nnadi 2023). Increasingly, firms integrate ESG considerations into their operations and innovation strategies in response to regulatory pressures and market expectations (Chen and Xie 2022). Existing studies suggest that ESG may influence firm behavior through channels such as reputation enhancement (Ruan et al. 2024), managerial awareness (Tan and Zhu 2022), and investment

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capacity (Mohy-ud-Din 2024). However, most research has focused on financial and market outcomes (Yu et al. 2025), with limited attention to how ESG affects firms' internal capability development and green innovation.

These limitations are particularly salient in the context of ongoing digital transformation and institutional changes promoting sustainable development. In China, policies related to green finance, carbon neutrality, and ESG disclosure have strengthened incentives for firms to align sustainability objectives with technological upgrading (Liu and Liu 2024; Ma et al. 2025). However, despite growing interest in ESG and sustainability, evidence on how ESG performance translates into green innovation remains limited. In particular, while digital transformation and information disclosure are recognized as important drivers of innovation (Li et al. 2022), their roles as integrated mediating channels in the ESG-innovation relationship are not well understood. Moreover, prior research has largely focused on average effects, with insufficient attention to heterogeneity across firms, industries, and regions.

To address these gaps, this study develops an integrated analytical framework that examines ESG-driven green innovation from three complementary perspectives: direct effects, internal capability-based mechanisms, and heterogeneous contextual conditions. Specifically, we investigate whether ESG performance promotes green innovation, through which internal channels this effect operates, and under what conditions it is strengthened. Using panel data on Chinese A-share listed firms from 2009 to 2023, we employ a two-way fixed effects model and an instrumental variable based on ESG fund exposure to strengthen causal identification. Digital transformation and information disclosure quality are incorporated as mediating variables to capture internal capability upgrading, and heterogeneity analyses are conducted across firm, industry, and regional dimensions.

This study makes three main contributions. First, it advances the literature on ESG and sustainable development by identifying how ESG performance translates into green innovation through capability transformation processes. Second, it provides new empirical evidence on the mediating roles of digital transformation and information disclosure and strengthens causal inference using an instrumental variable approach. Third, it highlights substantial heterogeneity in ESG effects across firms and contexts, offering more nuanced insights into when and where ESG strategies are most effective.

2 | Literature Review

With the growing global emphasis on sustainable development, the concept of ESG has gained increasing prominence in both corporate management and financial practice. A key question that has emerged in academic and practical discourse is how firms leverage ESG strategies to pursue green development. Existing research in this field can be broadly grouped into three main strands.

First, the relationship between ESG performance and firm performance has been examined within a relatively well-established

analytical framework. Studies have focused on the link between ESG and financial outcomes, finding that good ESG performance can enhance market valuation, reduce capital costs, and improve risk management capabilities (Friede et al. 2015; Margolis and Walsh 2003). Some scholars have further examined the implications of ESG in the Chinese context, showing that ESG ratings can partially reflect firms' future profitability (Li, Zhao, et al. 2024), attract fund allocations (Zhang et al. 2022), and alleviate external financing constraints (Chen et al. 2023). In addition, ESG has been shown to strengthen corporate reputational capital (Karwowski and Raulinajtys-Grzybek 2021) and employee satisfaction (Zhang et al. 2024), thereby enhancing organizational resilience and strategic execution capacity.

Second, in the research on the drivers of green innovation, a substantial body of research has explored the mechanisms influencing green technology output from the perspectives of institutional pressure, firm characteristics, and governance structures. Porter and van der Linde (1995) proposed the innovation-inducing effect of environmental regulation, which has since been supported by numerous empirical studies confirming the positive role of regulatory intensity, tax incentives, and green subsidies in promoting green innovation (Ambec et al. 2013). Meanwhile, factors such as firm size (Lin et al. 2019), ownership structure (Zhao, Zhao, et al. 2024), and organizational slack (Wu and Hu 2020) have been identified as important moderators of green innovation capacity. The institutional advantages and policy guidance enjoyed by state-owned enterprises in green investment have also attracted widespread attention (Li et al. 2020; Zhao, Ren, et al. 2024). Firm-level governance variables such as digital transformation (Li, Liu, and Hachard 2024), information disclosure quality (Li et al. 2022), and board structure (Qiu and Yu 2023) have also been increasingly incorporated into the analytical framework of green innovation.

Although green innovation is a multidimensional concept that may include organizational, managerial and process innovations, empirical research at the firm level often focuses on the technological output dimension of green innovation. In this context, green patent applications are widely used as observable indicators of environmentally oriented technological innovation (Flammer 2021). Patent data provide standardized, comparable, and longitudinal measures of firms' innovation activities, which makes them particularly suitable for firm-level panel analyses. International classification systems such as the OECD green patent taxonomy (Haščič and Migotto 2015) and the WIPO Green Inventory (León et al. 2017) further facilitate the identification of environmentally related technologies and allow researchers to systematically measure green innovation across firms and over time. Consequently, green patents have become a widely adopted proxy for firms' green innovation output in empirical studies.

Third, the direct relationship between ESG performance and green innovation has emerged as a growing focus of recent research. Recent studies have begun to document how ESG engagement contributes to firms' sustainable innovation performance. For example, Tan and Zhu (2022) and Wu et al. (2024) examine the relationship between ESG performance and corporate sustainable innovation using Chinese listed firms and show that ESG-oriented strategies can significantly enhance firms' sustainability-related innovation outcomes. Building on

this emerging line of research, scholars have argued that ESG strategies encourage firms to assume environmental responsibilities and social obligations, thereby strengthening their willingness to invest in green technologies and fostering a long-term orientation toward innovation (Flammer 2021; Xu, Yu, et al. 2023). On the other hand, strong ESG performance may also support green innovation by enhancing firms' external financing capacity (Wang and Sarkis 2017), attracting ESG fund investment, and increasing reputational capital (Flammer 2015). In the context of China, scholars have begun to explore the microeconomic effects of ESG, revealing that ESG can significantly improve firms' green patent output and green transition performance by enhancing governance efficiency, improving information disclosure (Zhang et al. 2020), and facilitating the integration of green strategies.

Although prior studies have confirmed the positive association between ESG performance and green innovation from multiple perspectives, several limitations remain. First, few studies systematically identify new mechanisms linking the two, particularly emerging micro-level channels such as digital transformation. Second, endogeneity in the relationship between ESG and green innovation has received limited attention, and effective identification strategies using exogenous instrumental variables are urgently needed to strengthen causal inference. Third, there is a lack of multi-level heterogeneity analyses across firm life cycles, industry structures, and regional development contexts, which leaves the practical implications of tailoring ESG strategies to specific firms and regions underexplored.

To address these gaps, this study develops an analytical framework that integrates ESG performance, green innovation outcomes, and mediating pathways. Using a two-way fixed effects model, together with instrumental variable and mediation analyses, the study empirically identifies the causal impact of ESG on green innovation. Furthermore, heterogeneity analyses across four dimensions, namely innovation type, firm characteristics, industry attributes, and regional context, provide more detailed and policy-relevant evidence.

3 | Theoretical Hypotheses

3.1 | ESG and Corporate Green Innovation

With the global advancement of sustainable development principles, corporate performance in ESG has become a vital indicator of long-term orientation and risk management capacity. From the perspective of dynamic capabilities theory, firms must continuously reconfigure their internal resources, governance structures, and strategic priorities in order to respond to evolving environmental and institutional pressures. In this context, ESG engagement can be understood as a strategic orientation that encourages firms to align their organizational capabilities with sustainability goals, thereby supporting green innovation. Firms with strong ESG performance often accumulate more intangible resources (Ioannou and Serafeim 2019), such as reputation capital, organizational identity, talent attraction, and better access to financing (Casciello et al. 2024; Deng et al. 2023; Flammer 2021; Li et al. 2023). These resource advantages provide important support for green innovation, enabling firms to pursue forward-looking technological development and systematic

innovation in the context of transitioning toward low-carbon, environment-friendly, and circular economy models. Within the dynamic capabilities framework, these intangible resources enhance firms' ability to sense sustainability challenges, seize green technological opportunities, and reconfigure organizational capabilities toward environmentally oriented innovation.

At the same time, in response to increasing environmental regulatory pressure and growing social responsibility expectations, firms often adopt visible actions such as green innovation to secure legitimacy and policy support (Li, Huang, et al. 2018). ESG performance, therefore, is not only a reflection of regulatory compliance but also demonstrates the firm's strategic proactiveness in pursuing green innovation. By embedding environmental and social considerations into strategic decision-making, ESG engagement encourages firms to redirect their technological trajectories toward sustainability-oriented innovation (Zhou et al. 2024). Moreover, the robust ESG strategy strengthens interactive trust between the firm and its stakeholders such as government entities, investors, customers, and local communities, thereby fostering a more stable and sustainable external cooperation network (Song and Ma 2025). This relational capital reduces the uncertainty surrounding green innovation in turn (Ruan et al. 2024), enhancing the efficiency of resource allocation and market recognition for such initiatives. These governance and relational advantages further support firms in mobilizing internal and external resources for green innovation, reinforcing the capability-building process emphasized by dynamic capabilities theory. Therefore, ESG not only functions as an external disclosure tool but also exerts a substantive influence on firms' internal green technology decisions and capabilities, ultimately enhancing their green innovation performance. Hence, hypothesis H1 is proposed:

H1. *Corporate ESG Engagement Positively Affects Green Innovation.*

3.2 | The Mediating Effects of Digitalization and Information Disclosure

The implementation of ESG strategies requires not only the fulfillment of environmental responsibilities, the strengthening of social governance, and the enhancement of transparency, but also imposes higher demands on corporate operations, data disclosure, and performance monitoring systems. These requirements have accelerated the adoption of digital technologies and digital infrastructure within firms. From the perspective of dynamic capabilities theory, firms confronted with increasing sustainability pressures must reconfigure their technological infrastructure and organizational processes in order to adapt to evolving environmental and institutional demands. In this process, digital technologies become a critical enabler that supports capability reconfiguration and organizational transformation. On one hand, strong ESG performance encourages firms to actively deploy digital technologies to achieve environmental goals, for example, building energy monitoring systems, carbon emission tracking platforms, and green supply chain systems. These digital applications enhance firms' capability to sense environmental risks and sustainability opportunities, enabling more precise monitoring and management of environmental performance. At the same

time, in the social and governance dimensions, firms also need to utilize big data and intelligent systems to enhance disclosure efficiency, employee coordination, and risk control, thereby driving a comprehensive digital transformation (Li et al. 2023). Through these processes, ESG engagement stimulates the upgrading of firms' digital infrastructure and managerial capabilities, facilitating the reconfiguration of internal resources emphasized by dynamic capabilities theory.

On the other hand, digital capability has become a foundational element for promoting green innovation. By integrating digital technologies, firms can more efficiently acquire green R&D data, optimize green product design, and improve resource efficiency and environmental friendliness in production processes (Fu and Xu 2024). Digital infrastructure further enables cross-departmental collaboration and open innovation in green projects, thereby enhancing both the quality and speed of green patent outputs (Zhang and Zhao 2023). In the dynamic capabilities framework, these digital capabilities strengthen firms' ability to integrate knowledge, coordinate innovation activities, and accelerate the commercialization of green technologies. In sum, ESG performance fosters improvements in firms' digital transformation capabilities, thereby establishing a technological support system for addressing sustainability challenges and indirectly enhancing green innovation performance. Hence, hypothesis H2 is proposed:

H2. *ESG positively influences green innovation through enhanced digital capabilities.*

ESG performance is closely associated with high-quality corporate information disclosure, which is a critical mechanism through which firms gain external trust and access to resources. Within the overall framework of dynamic capabilities theory, information disclosure can be viewed as an institutional governance mechanism that supports firms' capability reconfiguration by improving transparency and facilitating external resource mobilization. According to information asymmetry theory, improving disclosure quality can effectively reduce cognitive gaps between firms and external stakeholders, including investors, regulators, and the general public, enhance organizational transparency, and mitigate market uncertainty regarding green innovation projects (Healy and Palepu 2001). Green innovation often faces high capital requirements, uncertain return cycles, and significant external dependencies. As a signaling mechanism, high-quality disclosure communicates a firm's commitment to social and environmental responsibility and the credibility of its green innovation strategy to external parties (Tu, Wang, et al. 2025), thereby enhancing its reputation among green investors and government agencies (Alsaifi et al. 2020).

In addition, improvements in disclosure quality reinforce strategic alignment and long-term orientation among internal decision-makers, thereby facilitating institutional support and resource allocation for green research. By reducing information asymmetry and strengthening stakeholder confidence, transparent disclosure lowers the perceived risks associated with green innovation projects and improves firms' access to external capital and policy support. Firms with good ESG scores typically receive higher scores for information disclosure (Ben-Amar and McIlkenny 2015), which not only improves their ability to access

capital but also strengthens the effectiveness of strategic innovation execution (Liao 2018). Through these channels, enhanced disclosure quality supports the mobilization of financial, institutional, and knowledge resources required for green innovation. Therefore, ESG performance improves the transparency, completeness, and comparability of corporate disclosure, creating a more favorable institutional and resource environment for green strategies, and thereby indirectly enhancing green innovation performance. Hence, hypothesis H3 is proposed:

H3. *ESG positively influences green innovation through quality of information disclosure.*

3.3 | Heterogeneous Effects Across Innovation Output, Firm, Industry, and Region

Green innovation is not a unidimensional construct. Its outputs can be categorized into green invention patents, which emphasize technological originality, and green utility patents, which focus more on application and incremental improvements. The former generally reflect higher R&D intensity, technological complexity, and economic value, representing firms' long-term strategic investment and breakthrough capability in the process of green transformation.

From the perspective of strategic fit theory, the effectiveness of corporate sustainability strategies depends on the alignment between firms' strategic orientation and their innovation objectives. ESG engagement, as a long-term sustainability-oriented strategy, is more closely aligned with innovation activities that require sustained investment, complex technological capabilities, and long development cycles. Enterprises exhibiting robust ESG engagement tend to internalize sustainability strategies as guiding mechanisms for resource allocation and innovation direction (Flammer 2021). Through the coordinated functioning of environmental governance, social accountability, and corporate governance mechanisms, firms are more inclined to invest in long-term, systematic green R&D to generate high-value technological outcomes. Furthermore, green invention patents serve as external signals of technological capability and carry greater signaling value in obtaining policy support, attracting attention from capital markets and securing green certifications (Liu, Ahmad, et al. 2025). Motivated by reputational incentives and competitive advantage, firms are often more inclined to use ESG strategies to promote the production of high-quality green inventions, thereby strengthening their influence within the green market (Wu et al. 2021). Because green invention patents require deeper technological capabilities and longer innovation cycles, they exhibit a stronger strategic fit with firms that actively integrate ESG principles into their long-term innovation strategies. Hence, H4 is proposed:

H4. *The effect of corporate ESG on green invention patents is stronger than that on green utility patents.*

Firm-specific characteristics shape how organizations respond to external pressures and implement strategic actions, resulting in significantly heterogeneous effects across different types of firms. According to dynamic capabilities theory and strategic fit theory, firms' stages in the life cycle, ownership structure, and resource

base substantially influence their ability to absorb, transform, and reconfigure ESG strategies, thereby affecting the pathways and effectiveness through which ESG contributes to green innovation (Teece 2007). First, with respect to the corporate life cycle, firms in the decline stage often face challenges such as stagnant growth, intensifying competitive pressure, and loss of external support. Strategic transformation is urgently needed to revitalize organizational capacity (Tariq et al. 2019). In this context, ESG strategies may be viewed as effective tools for restoring reputation, acquiring policy resources, and reshaping market image. As a result, firms in the decline stage are more motivated to translate ESG performance into green innovation initiatives (Luo et al. 2023), demonstrating their commitment to sustainability and rebuilding market trust (Chen 2024). From the perspective of dynamic capabilities, such firms may rely on ESG-driven transformation to reconfigure their innovation strategies and regain competitiveness through green technological development.

Second, in terms of ownership structure, state-owned enterprises (SOEs) often bear more policy-driven responsibilities and social obligations (Tu, Zuo, et al. 2025), and they are more closely connected to government oversight, green finance policies, and public resource allocation (Wan et al. 2024). SOEs are under greater pressure from public supervision and information disclosure, which also encourages them to respond to ESG policy orientation and social expectations through green technology investment. These institutional linkages provide SOEs with stronger policy alignment and resource access, creating a favorable strategic fit for implementing ESG-driven green innovation strategies. Finally, in terms of firm size, large enterprises possess greater capacity for resource integration, technological reserves, and organizational coordination. These advantages enable more efficient conversion of ESG strategies into tangible green innovation outcomes. Compared to small and medium-sized enterprises (Tan et al. 2024), large firms typically have well-established environmental management systems and R&D platforms, and are more capable of attracting high-quality human capital and green financing, creating a fertile ground for systematic green innovation. Within the dynamic capabilities framework, these resource advantages strengthen large firms' ability to reconfigure technological and organizational capabilities in response to ESG-oriented sustainability goals. In sum, life cycle stage, ownership structure, and firm size jointly moderate the effectiveness and transformation mechanisms of ESG in promoting green innovation, leading to considerable variation in the marginal effects of ESG across different types of firms. Based on this, the following hypotheses are proposed:

H5. *The effect of ESG on green innovation varies across firm characteristics.*

H5a. *The effect of ESG on green innovation is more pronounced in firms at the decline stage.*

H5b. *The effect of ESG on green innovation is more pronounced in state-owned enterprises.*

H5c. *The effect of ESG on green innovation is more pronounced in large enterprises.*

The pollution intensity, market structure, and technological attributes of an industry fundamentally shape firms' strategic choices, resource allocation, and institutional responsiveness. As such, the green-innovation effect of ESG may exhibit systematic variation across different industries. From the perspective of strategic fit theory, the effectiveness of ESG-driven innovation strategies depends on whether the institutional and technological characteristics of an industry align with firms' sustainability-oriented strategic initiatives. Industries with stronger environmental pressures, resource advantages, or technological gaps may therefore exhibit stronger ESG-induced green innovation responses.

First, highly polluting industries face more stringent environmental regulations, greater public scrutiny (Liping Wu et al. 2024), and tighter policy constraints and are thus subject to higher compliance requirements within ESG evaluation systems (Porter and van der Linde 2000). Firms in these industries, driven by the need to secure legitimacy and protect their reputations, are more motivated to respond to ESG requirements through green innovation (Zhou et al. 2024), in order to reduce emissions risk, access green credit, and obtain government incentives. Under such institutional pressure, ESG engagement becomes more strongly aligned with firms' need to reconfigure production technologies and environmental management practices, thereby strengthening the strategic fit between ESG and green innovation. Therefore, the marginal effect of ESG on green innovation is expected to be stronger in high-pollution sectors (Xu, Li, and Guo 2023).

Second, in industries with high market concentration, firms face relatively less competitive pressure. They have stronger market control and more resources, tending to view ESG as a tool for building long-term competitive advantage rather than as short-term compliance costs (Weiss 2020). Firms in highly concentrated industries are also better positioned to accumulate capital, talent, and technological reserves necessary for green innovation and are also more willing to invest in green innovation (Wang et al. 2024) as a means of enhancing brand value and industry influence. These resource advantages enhance firms' dynamic capabilities in organizing and coordinating green innovation activities, allowing ESG strategies to be more effectively translated into technological innovation outcomes.

Third, non-digital industries, such as traditional manufacturing and heavy industries, typically lag behind in terms of green technology foundations and digital capabilities. For these firms, ESG strategies can help bridge the sustainability gaps in their existing technological trajectories and serve as key external drivers of green upgrading. In contrast, firms in digital industries are inherently more technologically sensitive and innovative, and their green innovation efforts are more often driven by technological inertia rather than ESG orientation. Consequently, the marginal effect of ESG incentives is relatively weaker in digital sectors (Li et al. 2023). In such contexts, ESG engagement plays a stronger catalytic role in industries with weaker technological foundations by encouraging firms to accelerate capability upgrading and green technological transformation. Differences in environmental sensitivity, market concentration, and technological foundation across industries significantly moderate the effectiveness of

ESG in boosting green innovation. Based on this, we propose the following hypotheses:

H6. *The effect of ESG on green innovation varies across industry types.*

H6a. *The effect of ESG on green innovation is more pronounced in high-pollution industries.*

H6b. *The effect of ESG on green innovation is more pronounced in industries with high market concentration.*

H6c. *The effect of ESG on green innovation is more pronounced in non-digital industries.*

The effect of corporate ESG performance on green innovation is shaped not only by firm-specific and industry-level factors, but also by the institutional environment, economic development level, and green resource endowment of the region in which a firm operates. From the perspective of strategic fit theory, the effectiveness of ESG-driven innovation strategies depends on whether the regional institutional environment and resource conditions support firms in translating sustainability commitments into technological innovation outcomes. In China, there has been a long-term pattern of “strong east and weak west” in regional development. The eastern region exhibits notable advantages in green governance foundations, technological supply capacity, and policy incentive systems. This spatial disparity provides important contextual conditions for the effective transformation of ESG strategies. First, green innovation is highly dependent on external institutional support, including the intensity of environmental regulation, the availability of green financial instruments (Wang and Sun 2022), and the presence of innovation subsidy mechanisms. The eastern region benefits from more mature institutions (Xu et al. 2025), more efficient governmental oversight, and stronger implementation of green development policies, enabling firms to more effectively convert ESG performance into institutional benefits and market recognition, thereby enhancing the marginal return on green innovation (Ma et al. 2025). In such institutional environments, ESG engagement is more strongly aligned with firms’ incentives to invest in green innovation, strengthening the strategic fit between corporate sustainability strategies and regional development policies.

Second, the eastern coastal region is home to a high concentration of universities, research institutions, green industrial clusters, and skilled talent, forming an innovation ecosystem that supports green technology advancement (Song and Ma 2025). Firms in this region benefit from stronger internal–external coordination, lower marginal costs of innovation, and more forward-looking and systematic responses to ESG strategies. These regional innovation advantages enhance firms’ dynamic capabilities in integrating knowledge resources and coordinating green innovation activities. Furthermore, green finance is more advanced in the eastern region, with more active markets for green credit, green bonds, and ESG investment funds. This implies that firms with higher ESG scores are more likely to obtain green financial resources, helping to alleviate the financial constraints and risk associated with green innovation (Liu, Ahmad, et al. 2025). By contrast, firms in the central and western areas face significant

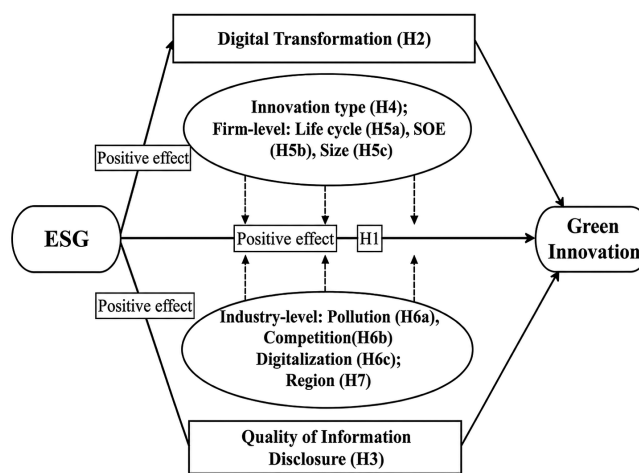


FIGURE 1 | Theoretical framework.

limitations in the institutional environment, resource availability, and green finance development. Even when motivated to adopt ESG strategies, such firms may lack sufficient external support to convert them into substantive green technological outcomes. Consequently, the strategic alignment between ESG engagement and green innovation incentives is weaker in these regions, leading to a relatively smaller marginal effect of ESG on green innovation. Hence, hypothesis H7 is proposed. Figure 1 illustrates the full framework of theoretical assumptions in this paper.

H7. *The effect of ESG on green innovation is stronger in the eastern region.*

4 | Research Design

4.1 | Data Sources

The analysis is based on panel data from Chinese A-share firms covering the years 2009 to 2023. Chinese A-share listed firms provide a suitable empirical setting for examining ESG-related corporate behavior because they are subject to relatively strict information disclosure requirements and standardized financial reporting rules. These institutional features enable researchers to obtain reliable and comparable firm-level data on ESG performance, innovation activities, and financial outcomes. In addition, A-share listed firms play a central role in China’s industrial and innovation systems, accounting for a substantial share of national R&D investment and patent outputs. As a result, they provide a meaningful empirical context for examining how ESG engagement influences firms’ green innovation. Firm-level variables were collected from the CSMAR and WIND databases (Liu and Liu 2024). ESG scores were obtained from the Huazheng ESG ratings and the WIND database. The data were processed using the following steps and exclusion criteria: (1) firms designated as ST or PT were removed, (2) observations with missing values for key variables were excluded, and (3) continuous variables were winsorized at the 1st and 99th percentiles to mitigate the influence of extreme values. After these procedures, the final sample comprised 42,832 firm-year observations.

4.2 | Variables

4.2.1 | Independent Variable

Table 1 shows the variable definitions. The core explanatory variable is the firm's ESG score (ESG). The ratings are classified into nine categories (C, CC, CCC, B, BB, BBB, A, AA, and AAA), which are converted into numerical values from 1 to 9 in ascending order. Since ESG ratings are released on a quarterly basis, each firm's annual ESG score is calculated as the average of its quarterly ratings within the year.

4.2.2 | Dependent Variable

Green innovation performance (Green_inno) is measured as the natural logarithm of one plus the number of annual green patent applications. Following prior studies, green patent applications are used to capture the technological output dimension of firms' green innovation activities, as patents data provide observable and standardized indicators of environmentally oriented technological innovation (Flammer 2021; León et al. 2017). Green patents are identified using the WIPO IPC Green Inventory, the CPC Y02 classification system, and the CNIPA Green Technology Patent Classification System. The logarithmic transformation is applied to reduce the influence of extreme values and address the skewed distribution of patent counts.

4.2.3 | Control Variables

To reduce potential bias from unobserved variables, we incorporate a set of firm-level controls according to existing studies (Hao and Wu 2024): revenue growth rate (Growth), shareholding concentration (Top1), return on assets (ROA), number of independent directors (IDN), nature of property rights (SOE), firm size

(Size), leverage (Lev), market-to-book ratio (Mbratio), and cash flow capacity (Cflow).

4.2.4 | Mediating Variables

Two mediating variables are introduced to capture internal mechanisms: the firm's information disclosure quality score (DIC), representing corporate information transparency, and the level of digital transformation (Digital), reflecting the firm's technological infrastructure and digitization capacity. The variable Digital is constructed using a text-based measurement approach based on the annual reports of listed companies, which are widely used to capture firms' digital transformation orientation in empirical studies (Rana et al. 2025). First, annual report PDFs of all A-share listed companies on the Shanghai and Shenzhen Stock Exchanges were collected using Python-based web crawlers. Textual content was then extracted using the Java PDFBox library to generate a raw text dataset.

To identify digital transformation signals in the textual data, a structured keyword dictionary was constructed based on both prior academic literature on enterprise digitalization and relevant national policy documents. Building on existing studies on digital transformation (Leal Filho et al. 2024; Li, Su, et al. 2018; Nambisan et al. 2017; Verhoef et al. 2021; Wu et al. 2020) and policy reports such as the SME Digital Empowerment Initiative, the Cloud Computing and Intelligent Transformation Action Plan, and the Digital Transformation Trends Report, a set of digital transformation keywords was compiled. Following this procedure, 76 digitalization-related keywords were identified and organized into five technological dimensions: artificial intelligence technology, big data technology, cloud computing technology, blockchain technology, and digital technology applications (Hongliang et al. 2024). These dimensions capture both foundational digital infrastructure and applied digital

TABLE 1 | Variable definitions.

Type	Variables	Symbol	Definition
Dependent variable	Green innovation performance	Green_inno	Log(1 + number of annual green patent applications of enterprises)
Independent variable	Corporate ESG ratings	ESG	Annual composite ESG score for each firm.
Control variables	Firm size	Size	Ln(total assets)
	Leverage	Lev	Total liabilities to total assets
	Market-to-book ratio	Mbratio	Market-to-book ratio
	Cash flow capacity	Cflow	Net operating cash flow to total assets
	Revenue growth rate	Growth	Annual growth rate of operating revenue
	Nature of property rights	SOE	Dummy variable of ownership type (1 = state-owned, 0 = non-state-owned).
	Shareholding concentration	Top1	Shareholding ratio of the largest shareholder
	ROA	ROA	Net income/total assets
Mediating variables	Number of independent directors	IDN	Number of independent directors
	Digital transformation	Digital	The firm's digital transformation score
	Information disclosure quality	DIC	Score of information disclosure

technologies commonly associated with firm digital transformation. The coding dictionary was iteratively refined and reviewed against terminology used in both the academic literature and official policy documents to improve conceptual consistency. In addition, sample annual reports were manually checked to ensure that retained keywords were contextually relevant to firm-level digital activities.

For each firm-year observation, the keyword dictionary was matched against the extracted annual report text, and the frequency of keyword occurrences across the five technological dimensions was counted and aggregated to construct a firm-level digital transformation indicator. To reduce potential ambiguity in textual expressions, several filtering procedures were implemented. First, keyword matches preceded by negation terms such as “no,” “not,” or “without” were excluded to avoid misclassification. Second, references to digital technologies appearing in non-firm contexts (e.g., descriptions of shareholders, customers, suppliers, or executive biographies) were removed to ensure that the indicator reflects the firm’s own digital activities. This dictionary-based approach enables a systematic and replicable identification of digital transformation signals in corporate disclosures. As with other text-based measures, the indicator captures firms’ digital transformation orientation as communicated in annual reports rather than the exact level of technology adoption. Given the right-skewed distribution of term frequencies, the natural logarithm of one plus the aggregated keyword frequency was used to construct the Digital variable.

The second mediating variable, DIC, measures firms’ information disclosure quality. This indicator is obtained from the information disclosure evaluation system reported in the integrity files of the Shenzhen Stock Exchange. These ratings are assigned by the exchange based on firms’ compliance with disclosure regulations, the timeliness of reporting, and the completeness and accuracy of disclosed information. Following Ouyang and Hu (2024), the ratings are coded on an ordinal scale from 1 to 4, where higher values indicate better disclosure quality and greater corporate transparency. Because the information disclosure evaluation data are provided by the Shenzhen Stock Exchange, this variable is available only for firms listed on that exchange. Accordingly, the sample size for analyses involving DIC is smaller than that used in the benchmark regressions.

4.3 | Model and Methodology

To empirically assess the effect of ESG performance on green innovation, this study employs a two-way fixed effects model that controls for both firm and year fixed effects. Standard errors are clustered at the city level to account for potential intra-regional correlations. The econometric specification is as follows:

$$Green_inno_{it} = \alpha + \beta \cdot ESG_{it} + X'_{it}\gamma + \delta_i + \varphi_t + \varepsilon_{it} \quad (1)$$

where $Green_inno_{it}$ denotes the green innovation performance of firm i in year t , measured as the logarithm of one plus the number of green patent applications; ESG_{it} represents the firm’s ESG score and serves as the key explanatory variable; X_{it} is a vector of control variables; δ_i and φ_t denote firm and year fixed effects, respectively, and ε_{it} is the error term.

To further investigate the mediating mechanisms through which ESG performance affects green innovation outcomes, this study applies a mediation analysis framework to identify the roles of information disclosure quality and digital transformation. The mediating models are specified as follows:

$$Digital_{it} = \alpha_0 + \beta_0 ESG_{it} + X'_{it}\gamma + \delta_i + \varphi_t + \varepsilon_{it} \quad (2)$$

$$Green_inno_{it} = \alpha_0 + \beta_0 ESG_{it} + \beta_1 Digital_{it} + X'_{it}\gamma + \delta_i + \varphi_t + \varepsilon_{it} \quad (3)$$

$$DIC_{it} = \alpha_0 + \beta_0 ESG_{it} + X'_{it}\gamma + \delta_i + \varphi_t + \varepsilon_{it} \quad (4)$$

$$Green_inno_{it} = \alpha_0 + \beta_0 ESG_{it} + \beta_1 DIC_{it} + X'_{it}\gamma + \delta_i + \varphi_t + \varepsilon_{it} \quad (5)$$

5 | Empirical Results

5.1 | Descriptive Statistics

Descriptive statistics are reported in Table 2. Green innovation ($Green_inno$) has a mean of 0.826 and a standard deviation of 1.163 (range: 0–5.252), indicating substantial variation across firms, with most firms exhibiting relatively low green patent output. The average ESG score is 4.135 (SD = 0.966), suggesting moderate ESG performance with notable dispersion. The Pearson correlation matrix (Table 3) shows that most pairwise correlations are relatively low, suggesting a low level of pairwise correlation among variables.

5.2 | Benchmark Regression

Table 4 reports the baseline regression results on the relationship between ESG performance and green innovation. In Column (1), ESG is positively associated with green innovation ($\beta = 0.195, p < 0.01$). After including firm and year fixed effects in Column (2), the coefficient decreases to 0.083 but remains significant at the 1% level. In Column (3), after adding control variables, the coefficient further declines to 0.060 yet remains positive and highly significant, indicating that ESG is an important driver of green innovation. Specifically, a one-point increase in ESG is associated with approximately a 6% increase in green

TABLE 2 | Descriptive Statistics.

Variables	N	Mean	Std. dev.	Min	Max
Green_inno	42,832	0.826	1.163	0.000	5.252
ESG	42,832	4.135	0.966	1	8
Top1	42,832	34.121	14.918	7.430	77.020
Size	42,832	22.238	1.425	18.171	27.268
Lev	42,832	0.433	0.220	0.031	1.893
Mbratio	42,832	0.623	0.251	0.056	1.258
Cflow	42,832	0.046	0.073	-0.289	0.355
Growth	42,832	0.384	1.211	-0.969	17.107
ROA	42,832	0.032	0.240	-0.709	0.360
SOE	42,832	0.364	0.481	0	1
IDN	42,832	3.172	0.614	0	9

TABLE 3 | Pearson correlation matrix.

Variables	Green_inno	ESG	Top1	Size	Lev	Mbratio	Cflow	Growth	ROA	SOE	IDN
Green_inno	1.000										
ESG	0.162***	1.000									
Top1	0.040***	0.108***	1.000								
Size	0.416***	0.258***	0.174***	1.000							
Lev	0.168***	-0.109***	0.014***	0.468***	1.000						
Mbratio	0.196***	0.146***	0.154***	0.569***	0.311***	1.000					
Cflow	0.018***	0.088***	0.097***	0.058***	-0.162***	-0.095***	1.000				
Growth	-0.025***	-0.016***	0.017***	-0.021***	0.060***	-0.005***	-0.088***	1.000			
ROA	0.009***	0.217***	0.149***	0.010**	-0.355***	-0.129***	0.363***	0.020***	1.000		
SOE	0.115***	0.053***	0.207***	0.364***	0.298***	0.236***	-0.007***	0.041***	-0.017***	1.000	
IDN	0.116***	0.131***	0.050***	0.374***	0.209***	0.190***	0.023***	-0.013***	0.002	0.293***	1.000

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

TABLE 4 | Benchmark regression.

	(1) Green_inno	(2) Green_inno	(3) Green_inno
ESG	0.195*** (0.006)	0.083*** (0.008)	0.060*** (0.007)
Controls	No	No	Yes
Firm	No	Yes	Yes
Year	No	Yes	Yes
Adj. R ²	0.026	0.681	0.694
N	42,832	42,832	42,832

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. City-clustered robust standard errors are shown in parentheses.

innovation (in logarithmic terms), supporting Hypothesis 1. This result is consistent with previous studies showing that stronger ESG engagement can significantly promote firms' sustainability-oriented development (Song and Ma 2025; Wu et al. 2024; Zhou et al. 2024).

To further identify the pathways linking ESG activities to green innovation, the ESG score is disaggregated into its three core components: Environmental (E), Social (S), and Governance (G). The results reported in Table 5 indicate that all three dimensions exert a significantly positive impact on green innovation at the 1% level. Among them, the environmental dimension has a relatively larger marginal effect, with a coefficient of 0.037, indicating that stronger environmental responsibility can be more directly translated into higher green innovation output. This may reflect the role of firms' investments in pollution control, energy conservation, and environmental management systems, which can be transformed into tangible technological achievements (Ambec et al. 2013; Li, Huang, et al. 2018).

The social and governance dimensions also have positive and significant effects, with coefficients of 0.026 and 0.022, respectively. The social dimension highlights the contribution of employee welfare, product safety, and community engagement to building trust among investors and stakeholders, which facilitates access to innovation-related resources (Karwowski and Raulinajtyś-Grzybek 2021; Luo et al. 2023). The governance

TABLE 5 | ESG subscores and green innovation.

	(1) Green_inno	(2) Green_inno	(3) Green_inno
E score (Environmental)	0.037*** (0.004)		
S score (Social)		0.026*** (0.003)	
G score (Governance)			0.022*** (0.004)
Controls	Yes	Yes	Yes
Firm	Yes	Yes	Yes
Year	Yes	Yes	Yes
Adj. R ²	0.694	0.693	0.693
N	42,831	42,157	42,750

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. City-clustered robust standard errors are shown in parentheses.

dimension underscores the importance of board oversight, internal controls, and anti-corruption measures in supporting innovation capacity. Such governance mechanisms have been widely recognized as institutional foundations that promote sustainable innovation and long-term corporate performance (Ioannou and Serafeim 2019; Wang and Sarkis 2017).

5.3 | Mediating Effect of Digitalization and Information Disclosure

A stepwise regression approach is applied to test the mediating effects, and the results are presented in Table 6. In Column (2), the coefficient of ESG on digital transformation is 0.015 and significant at the 5% level, indicating that ESG performance enhances firms' digitalization levels. This result is consistent with previous studies suggesting that ESG-oriented strategies can encourage firms to strengthen their digital transformation and organizational upgrading (Li et al. 2023; Xu, Yu, et al. 2023). In Column (3), after including digital transformation, the ESG coefficient declines to 0.056, suggesting a partial mediating effect. This finding indicates that ESG promotes green innovation in part

TABLE 6 | Mediating effect of digitalization and information disclosure.

	(1) Green_inno	(2) Digital	(3) Green_inno	(4) DIC	(5) Green_inno
ESG	0.060*** (0.007)	0.015** (0.008)	0.056*** (0.008)	0.099*** (0.007)	0.047*** (0.009)
Digital			0.043*** (0.009)		
DIC					0.024** (0.011)
Controls	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Adj. R ²	0.694	0.769	0.701	0.455	0.723
N	42,832	39,198	38,966	30,281	30,281

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. City-clustered robust standard errors are shown in parentheses. The DIC-based models are estimated on the available Shenzhen Stock Exchange subsample because information disclosure quality data are obtained from the exchange's integrity files.

TABLE 7 | Bootstrap results.

Mediating variable	(1) Indirect effect	(2) Direct effect
Digital	0.0109*** (0.0009)	0.0578*** (0.0052)
DIC	0.0184*** (0.0021)	0.0749*** (0.0068)

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. Bootstrap standard errors are shown in parentheses.

by strengthening firms' digital capabilities, thereby supporting Hypothesis 2.

In Column (4), the coefficient of ESG on information disclosure quality is 0.099 and significant at the 1% level, indicating that ESG implementation improves firms' information transparency. Because the information disclosure quality data are obtained from the integrity files of the Shenzhen Stock Exchange, the DIC-based mediation analysis is estimated on the available subsample of 30,281 firm-year observations. In Column (5), after including DIC, the ESG coefficient further decreases to 0.047, again demonstrating a significant partial mediating effect. This result further suggests that ESG promotes green innovation by improving the quality of information disclosure, thereby providing support for Hypothesis 3. Such a mechanism is in line with prior research emphasizing that stronger disclosure quality can reduce information asymmetry and support firms' innovation-related activities (Healy and Palepu 2001; Li et al. 2022). Bootstrap results (Table 7, 500 resamples) confirm that both indirect effects are significant at the 1% level, supporting the mediating hypotheses.

5.4 | Multidimensional Heterogeneity Analysis

Table 8 reports the heterogeneity results across green innovation types and regions. Across all subgroups, ESG consistently exerts

a significantly positive effect on green innovation, with all coefficients significant at the 1% level. However, the magnitude of the effects varies, suggesting heterogeneous patterns across different innovation types and regional contexts. Columns (1) and (2) show the results by innovation type. ESG has a larger estimated effect on green invention patents (0.055) than on utility patents (0.041), highlighting its role in stimulating higher-quality and knowledge-intensive innovation (Song and Ma 2025; Tan et al. 2024). These findings suggest that ESG performance promotes not only broader participation in green innovation but also higher-value technological outputs, thereby providing evidence consistent with Hypothesis 4. Columns (3), (4), and (5) present the results by region. The ESG coefficient is positive and statistically significant across all three regions, with the eastern region showing a slightly larger estimated coefficient (0.062), followed by the western (0.058) and central (0.052) regions. These observed patterns may reflect variations in institutional maturity, policy implementation capacity, and the availability of green finance across regions, factors that have been widely recognized as important contextual conditions shaping firms' green innovation performance (Ma et al. 2025; Yu et al. 2025). Overall, these results are broadly consistent with Hypothesis 7 and point to a suggestive regional pattern in which the ESG–green innovation association appears somewhat stronger in the eastern region.

Table 9 reports the heterogeneous effects across firm characteristics. Regarding the corporate life cycle, the ESG coefficient is largest in the decline stage (0.088), followed by the maturity stage (0.054) and the growth stage (0.047). This pattern suggests that firms facing stronger survival pressure may be more inclined to adopt ESG as a strategic instrument to restore competitiveness and organizational legitimacy, thereby providing evidence consistent with Hypothesis 5a. This pattern is broadly consistent with studies showing that firms at different life cycle stages exhibit varying innovation incentives and strategic responses (Tariq et al. 2019).

In terms of ownership, state-owned enterprises (SOEs) have a slightly larger estimated ESG coefficient (0.056) compared with

TABLE 8 | Heterogeneous effects analysis of green innovation types and regions.

	Green innovation types		Regions		
	(1) Green invention patents	(2) Green utility patents	(3) Eastern region	(4) Central region	(5) Western region
ESG	0.055*** (0.006)	0.041*** (0.008)	0.062*** (0.009)	0.052*** (0.016)	0.058*** (0.018)
Controls	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes
Adj. R ²	0.665	0.645	0.711	0.658	0.671
N	42,832	42,832	30,648	6,341	5,299

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. City-clustered robust standard errors are shown in parentheses.

TABLE 9 | Heterogeneous effects analysis of firm characteristics.

	Life stage			Ownership		Firm size	
	(1) Growth	(2) Maturity	(3) Decline	(4) SOEs	(5) Non-SOEs	(6) Small	(7) Large
ESG	0.047*** (0.012)	0.054*** (0.012)	0.088*** (0.012)	0.056*** (0.011)	0.047*** (0.010)	0.026*** (0.008)	0.064*** (0.010)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adj. R ²	0.695	0.717	0.676	0.747	0.654	0.578	0.744
N	17,965	14,295	7,568	15,552	27,210	21,139	21,360

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. City-clustered robust standard errors are shown in parentheses.

non-SOEs (0.047), reflecting the institutional embeddedness and policy responsiveness of SOEs within China’s regulatory context, thereby providing evidence consistent with Hypothesis 5b. Such a pattern is consistent with prior research indicating that state ownership can strengthen firms’ responsiveness to environmental policies and green innovation initiatives (Zhao, Zhao, et al. 2024). With respect to firm size, large enterprises show a larger estimated ESG coefficient (0.064) relative to smaller firms (0.026). This finding may reflect differences in R&D capacity, financial resources, and ESG implementation capability between large and small firms, providing evidence consistent with Hypothesis 5c.

Table 10 presents the heterogeneous effects across industry attributes. With respect to pollution intensity, ESG shows a larger estimated coefficient in high-pollution industries (0.071) than in non-high-pollution sectors (0.054). This finding suggests that external regulatory pressure may amplify the strategic importance of ESG in environmentally sensitive industries, thereby providing evidence consistent with Hypothesis 6a. This interpretation is consistent with prior research indicating that environmental regulation and institutional pressure can stimulate firms’ green innovation activities, particularly in pollution-intensive sectors (Ambec et al. 2013; Zhao, Zhao, et al. 2024).

In terms of digitalization, non-digital industries display a larger estimated ESG coefficient (0.061) compared with digital industries (0.041). This result suggests that ESG may play a compensatory role in less technology-intensive sectors where innovation inertia tends to be stronger (Xu, Yu, et al. 2023), providing evidence consistent with Hypothesis 6c. Regarding market competition, the ESG effect is larger in low-competition industries (0.072) relative to high-competition ones (0.051). This pattern may reflect that firms operating in industries with greater market power and resource slack have a stronger capacity to integrate ESG considerations into innovation strategies (Weiss 2020; Wu and Hu 2020), thereby providing evidence consistent with Hypothesis 6b.

5.5 | Endogeneity

Given the potential for reverse causality, which may lead to endogeneity concerns, we employ an instrumental variable (IV) approach. The IV approach helps isolate the exogenous variation in ESG performance and is widely used to address potential simultaneity and omitted variable bias in corporate finance and innovation research (Angrist and Pischke 2009; Wooldridge 2010). The selected instruments are whether a firm is held by ESG investment funds (L.ESGFunder), the number of

TABLE 10 | Heterogeneous effects analysis of industry attributes.

	Pollution intensity		Digital industry		Market competition	
	(1) High	(2) Non-high	(3) Digital	(4) Non-digital	(5) High	(6) Low
ESG	0.071*** (0.016)	0.054*** (0.008)	0.041** (0.017)	0.061*** (0.008)	0.051*** (0.011)	0.072*** (0.011)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
Adj. R ²	0.652	0.715	0.693	0.699	0.709	0.720
N	11,180	31,613	7,718	35,087	21,250	19,320

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. City-clustered robust standard errors are shown in parentheses. Low competition indicates high market concentration.

ESG funds holding the firm (L.ESGfunder number), and the market value of ESG fund holdings (L.ESGfunder value). All instruments are lagged by one period to mitigate simultaneity bias. ESG investment funds are defined as funds that systematically incorporate environmental, social, and governance factors into investment decisions, and their investment behavior reflects the market’s external recognition of a firm’s ESG performance. These instruments are strongly correlated with ESG levels and are plausibly exogenous to firms’ green innovation outcomes, thereby satisfying the relevance and exogeneity conditions required for valid instrumental variables.

Table 11 reports the two-stage least squares (2SLS) regression results using the three measures of instrumental variables. The first-stage regressions show that all instruments have significantly positive effects on ESG performance at the 1% level, with F-statistics well above the conventional threshold of 10, which is commonly used to diagnose weak instruments in IV estimation. This indicates strong explanatory power and satisfies the relevance condition for valid instruments (Stock and Yogo 2002). The second-stage regressions demonstrate that, after addressing endogeneity, the effect of ESG on green innovation remains statistically significant. The coefficients range from 1.024 to 1.062, all at the 1% significance level, which supports the positive relationship between ESG performance and green innovation after accounting for potential endogeneity.

It should be noted that the IV estimates are substantially larger than the benchmark TWFE estimate of 0.060. This divergence may be explained by several factors. First, the OLS estimate may be relatively conservative because rating-based ESG measures, while widely used in empirical research, may contain some degree of measurement noise and may not fully capture all dimensions of firms’ underlying sustainability practices. Second, the IV estimates may reflect the effect of ESG among firms whose ESG performance is more responsive to ESG fund investment. These firms may be more likely to translate ESG-related external recognition, investor attention, and capital market support into green innovation activities. In this sense, the IV estimates may capture a local effect associated with ESG fund-induced variation, rather than a directly comparable average marginal effect for the full sample. Therefore, the IV results are best viewed as complementary evidence supporting the positive direction and

statistical significance of the ESG effect, while the magnitude of the estimates should be interpreted with appropriate caution.

5.6 | Robustness Tests

To assess robustness, we conduct alternative specifications using different ESG measures, data sources, and dependent variables (Table 12). In Column (1), ESG is measured by its median value of quarterly ESG ratings (ESGmedian), and the coefficient remains positive and significant (0.052, $p < 0.01$). In Columns (2) and (3), ESG data are obtained from the Wind database using raw scores (ESGWind1) and rank scores (ESGWind2), both of which yield positive and significant coefficients. In Column (4), green innovation is measured using granted green patents, and the ESG coefficient remains positive and significant (0.045, $p < 0.01$). Overall, the results are robust across alternative measures and data sources, confirming the stability of the baseline findings.

6 | Conclusion and Discussion

This study examines the impact of ESG performance on green innovation using a panel dataset of Chinese A-share listed companies. The results show that corporate ESG performance significantly enhances green innovation output, suggesting that ESG strategies not only fulfill compliance and reputational functions but also serve as strategic drivers of sustainability-oriented technological upgrading by reshaping firms’ resource allocation, governance structures, and innovation priorities. This conclusion remains robust across alternative ESG measures, data sources, definitions of green innovation, and instrumental variable estimations. These results are consistent with recent studies indicating that ESG engagement can promote corporate green innovation and sustainability-oriented technological transformation (Liu, Long, et al. 2025; Song and Ma 2025; Wu et al. 2024).

In the mediating effects analysis, our findings highlight two complementary organizational mechanisms through which ESG engagement influences green innovation. First, ESG performance promotes digital transformation, which improves firms’ technological capabilities and supports the development and implementation of green innovation activities. Second, ESG

TABLE 11 | Instrumental variables regression.

	(1) First stage ESG	(2) Second stage Green_inno	(3) First stage ESG	(4) Second stage Green_inno	(5) First stage ESG	(6) Second stage Green_inno
L.ESGfunder number	0.005*** (0.001)					
L.ESGfunder value			0.004*** (0.0001)			
L.ESGfunder					0.082*** (0.009)	
ESG		1.062*** (0.186)		1.024*** (0.179)		1.038*** (0.186)
SW-F	87.360		89.180		78.220	
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes	Yes	Yes
N	36,736	36,736	36,736	36,736	36,736	36,736

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. City-clustered robust standard errors are shown in parentheses.

TABLE 12 | Robustness tests.

	(1) Median Green_inno	(2) Wind data Green_inno	(3) Wind data Green_inno	(4) Granted-patent number Green_inno
ESGmedian	0.052*** (0.006)			
ESGWind1		0.010*** (0.001)		
ESGWind2			0.045*** (0.006)	
ESG				0.045*** (0.007)
Controls	Yes	Yes	Yes	Yes
Firm	Yes	Yes	Yes	Yes
Year	Yes	Yes	Yes	Yes
Adj. R ²	0.694	0.694	0.694	0.685
N	42,832	42,832	42,832	42,832

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels. City-clustered robust standard errors are shown in parentheses.

performance improves the quality of corporate information disclosure, which reduces information asymmetry between firms and external stakeholders. By enhancing transparency and credibility, stronger disclosure quality can increase stakeholder trust, facilitate access to financial resources and policy support, and reduce uncertainty surrounding green innovation investments (Healy and Palepu 2001; Li et al. 2022). These findings are consistent with prior studies showing that disclosure and transparency can enhance firms' green innovation performance (Ruan et al. 2024). In this sense, ESG engagement contributes not only to

capability upgrading within firms but also to the improvement of the informational environment in which green innovation takes place (Li, Liu, and Hachard 2024; Xu, Yu, et al. 2023).

The heterogeneity analysis reveals notable variation in ESG's green innovation effects across innovation types, firm characteristics, industry attributes, and regional contexts. ESG has a stronger impact on invention patents than on utility patents, underscoring its role in promoting high-quality, original innovation (Zhou et al. 2024). At the firm level, the effect is more

pronounced among firms in the decline stage, state-owned enterprises, and large firms, suggesting that life cycle stage, ownership, and resource capacity shape the ESG–innovation link (Tariq et al. 2019; Zhao, Zhao, et al. 2024). At the industry level, ESG exerts greater marginal effects in high-pollution, non-digital, and highly concentrated sectors, indicating that external regulatory pressure, technological readiness, and market structure condition its impact (Ambec et al. 2013). Regionally, the effect is strongest in eastern China, highlighting the enabling role of institutional quality and the concentration of green innovation resources.

The empirical findings of this research generate several theoretical, managerial, and policy implications for advancing ESG-driven green innovation. From a theoretical perspective, this study contributes to the growing literature on ESG and sustainable innovation by clarifying the mechanisms through which ESG engagement influences firms' green technological outcomes. By integrating dynamic capabilities theory (Teece 2007) with information asymmetry perspectives (Healy and Palepu 2001) and strategic fit perspectives, the study develops an analytical framework linking ESG engagement, digital transformation, information disclosure, and green innovation. This framework advances the literature by positioning ESG engagement as a driver of capability transformation, explaining how sustainability-oriented strategies reshape firms' internal structures and innovation processes.

From a managerial perspective, firms should establish sustainability strategies grounded in ESG principles and embed them into long-term technological development planning. Strengthening ESG disclosure systems and improving green credit and investment incentives can help translate ESG initiatives into long-term commitments to technological innovation (Chen et al. 2023). In addition, promoting the integration of ESG strategies with corporate digital transformation is particularly important. At the operational level, firms should further promote the integration of ESG strategies with digital transformation initiatives. Initiatives such as cloud adoption, data utilization, and intelligent empowerment can enhance firms' governance capacity and information transparency, thereby forming a dual engine of technological capability and governance improvement that supports sustainable development (Xu, Yu, et al. 2023).

From a policy perspective, ESG incentive systems should be tailored to firm characteristics. Declining-stage, large-scale, and state-owned enterprises should be supported with targeted resources and policy tools to strengthen their motivation for green innovation. High-pollution and resource-intensive industries should be encouraged to embed ESG principles into technological upgrading, shifting from compliance-oriented behavior toward innovation-driven transformation (Ambec et al. 2013). At the institutional level, governments can further strengthen ESG-related regulatory frameworks and green finance mechanisms to provide stable incentives for firms to integrate ESG strategies into long-term innovation activities. In addition, regional ESG capacity-building should be advanced in line with local conditions. While consolidating the ESG–innovation link in the eastern region, greater investment is needed in the central and western regions to expand green finance and enhance ESG

implementation capacity, thereby promoting more balanced regional development in green innovation.

Beyond the specific empirical context of Chinese A-share listed firms, this study also provides broader insights into how ESG engagement may influence sustainability-oriented innovation across different institutional environments. In particular, the results suggest that improvements in digital capabilities and corporate transparency constitute key organizational mechanisms linking ESG strategies to green innovation. These mechanisms, including capability upgrading, transparency enhancement, and stakeholder alignment, represent general organizational processes that are not unique to Chinese listed firms but may operate across different economic systems (Li et al. 2022). Therefore, the analytical framework developed in this study may offer useful insights for understanding ESG-driven innovation among firms in other emerging and developed economies, including non-listed firms and small and medium-sized enterprises. By clarifying these mechanisms, this study contributes to a broader understanding of how ESG-oriented corporate strategies can foster green innovation and support long-term sustainable development.

Several limitations should be acknowledged. First, green innovation is measured using patent-based technological outputs, which capture the technological dimension of environmental innovation but may not fully reflect other forms such as organizational or process-related green innovation. Second, this study focuses on Chinese A-share listed firms, which may limit the generalizability of the findings to other types of firms or institutional environments. Listed firms are typically larger and more resource-rich than small and medium-sized enterprises, and their ESG practices may therefore differ from those of non-listed firms. Third, the information disclosure quality variable is obtained from the integrity files of the Shenzhen Stock Exchange and is therefore available only for firms listed on that exchange. As a result, the mediation analysis involving information disclosure quality is based on a smaller subsample than the benchmark regressions. Although this analysis provides useful evidence on the information disclosure mechanism, the results should be interpreted with appropriate caution, as this subsample may not fully represent the broader sample used in the main analysis. Fourth, the heterogeneity analyses are based on subgroup regressions and are intended to identify suggestive patterns across patent types, firm, industry, and regional contexts. Although the results show meaningful variation in the estimated ESG coefficients, especially across firm size, industry attributes, and regions, these coefficient differences should be interpreted with appropriate caution. Future research could extend the analysis to privately held firms, SMEs, firms listed on different exchanges, or firms operating in different institutional contexts to further examine the generalizability of ESG-driven green innovation mechanisms.

Author Contributions

Yingying Ouyang: writing – original draft, software, methodology, formal analysis, data curation, conceptualization, visualization, writing – review and editing. **Yifan Zhang:** writing – original draft. **Rongrong Ouyang:** writing – original draft, formal analysis. **Xin Ye:** writing – review and editing. **Mingzheng Hu:** writing – review and editing, supervision.

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Ethics Statement

The authors have nothing to report.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets used during the current study are available from the corresponding author on reasonable request.

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