Employees' AI Literacy and Green Innovation Efficiency: The Mediating Role of Dynamic Capabilities and the Moderating Effect of ESG Performance in Chinese Listed Firms

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Abstract

This study aimed to (1) examine the impact of employees' AI literacy on green innovation efficiency in Chinese listed firms, (2) investigate the mediating role of dynamic capabilities, and (3) analyze the moderating effect of environmental, social, and governance (ESG) performance on this relationship. The research employed a quantitative research design using panel data analysis. The sample consisted of 15,700 firm-year observations from Chinese A-share listed companies during the period 2015–2021, selected through purposive sampling based on data availability and completeness. The research instruments were constructed from secondary data sources, including corporate annual reports, ESG rating databases, and financial and patent databases. Employees' AI literacy was measured using text mining and word frequency analysis, while green innovation efficiency, dynamic capabilities, and ESG performance were operationalized using established indices.

Statistical analyses included descriptive statistics, correlation analysis, fixed-effects regression, mediation analysis, moderation analysis, and moderated mediation analysis. The results indicated that employees' AI literacy had a significant positive effect on green innovation efficiency. Dynamic capabilities were found to play a mediating role in this relationship, demonstrating that AI literacy enhances firms' ability to integrate, adapt, and reconfigure resources, thereby improving innovation outcomes. Furthermore, ESG performance significantly moderated both the direct and indirect relationships, strengthening the positive impact of AI literacy on green

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innovation efficiency through dynamic capabilities. Additional heterogeneity analysis revealed that the effects were more pronounced in high-tech firms and varied across regions, with the strongest impact observed in central China. The findings contribute to theoretical and practical knowledge by highlighting employees' AI literacy as a critical micro-level driver of green innovation efficiency and by integrating dynamic capability theory with ESG frameworks. The study suggests that firms should invest in enhancing employees' AI competencies, strengthen organizational dynamic capabilities, and foster ESG-oriented governance environments to maximize green innovation performance. These insights provide valuable guidance for policymakers and corporate managers in promoting sustainable development through the synergistic integration of human capital, organizational capabilities, and sustainability strategies.

Keywords: Green Innovation Efficiency; AI Literacy; Dynamic Capability; Environmental, Social and Governance (ESG)

Introduction

In the context of accelerating global climate change and increasing environmental constraints, achieving sustainable development through green transformation has become a central priority for both governments and enterprises worldwide. The need to balance economic growth with ecological protection has intensified, making green technological innovation a critical pathway for promoting sustainable industrial development and improving environmental governance (Islam, 2025; Tu, et al., 2024). Green innovation not only mitigates environmental degradation caused by excessive resource consumption and pollution but also enhances long-term competitiveness by fostering efficient resource utilization and technological advancement (Bilal, et al., 2021; Zhao, et al., 2025). Within this transformation process, firms particularly listed companies play a pivotal role as primary drivers of green innovation due to their capacity for resource integration, technological investment, and strategic decision-making (Tang, et al., 2023; Yan, et al., 2021). In recent years, the rapid development of artificial intelligence (AI) has further reshaped the innovation landscape, providing new opportunities to enhance green innovation efficiency through data-driven decision-making and intelligent resource optimization (Wang, et al., 2025). While prior research has largely focused on firm-

level AI adoption and digital transformation, growing attention has been directed toward employees' AI literacy as a micro-level human capital factor that underpins the effective utilization of AI technologies (Hussain, 2025). From the perspective of dynamic capability theory, firms' ability to sense, seize, and reconfigure resources in response to environmental changes is essential for sustaining competitive advantage in dynamic environments (Teece, et al., 1997; Ambrosini & Bowman, 2009). Consequently, understanding how employees' AI literacy contributes to green innovation efficiency through organizational capabilities has become an important area of inquiry in both strategic management and sustainability research.

Despite the growing body of literature on AI and green innovation, several critical gaps remain. First, existing studies predominantly emphasize technological and institutional determinants of green innovation such as digital infrastructure, environmental regulation, and policy incentives while largely overlooking the role of employee-level capabilities in shaping innovation outcomes (Rachmatulloh, et al., 2025; Billi & Bernardo, 2025). Given that employees are the direct actors who implement technological processes and translate digital tools into innovative practices, neglecting AI literacy as a human capital resource limits our understanding of how technological potential is realized at the organizational level. Second, although dynamic capabilities have been widely recognized as key mechanisms for enhancing firm performance and innovation (Ferreira, et al., 2021; Li, et al., 2023), limited research has examined their mediating role in linking employee AI literacy to green innovation efficiency. This gap is particularly important because AI literacy alone may not directly lead to innovation outcomes unless it is effectively embedded within organizational processes and capabilities. Third, while environmental, social, and governance (ESG) performance has emerged as a crucial indicator of corporate sustainability and responsible governance (Rajesh & Rajendran, 2020; Tyan, et al., 2024), its role as a contextual boundary condition influencing the effectiveness of internal capabilities remains underexplored. ESG performance reflects a firm's commitment to sustainability and governance quality, which may enhance the translation of employee competencies into innovation outcomes by providing supportive institutional and cultural environments. Therefore, there is a need for a more integrated framework that simultaneously considers employee AI literacy, dynamic capabilities, and ESG performance in explaining green innovation efficiency. Addressing these gaps is particularly relevant in the Chinese context, where rapid

digital transformation and strong policy support for green development create a unique setting for examining the interplay between technological capability, organizational processes, and sustainability performance (Stern & Xie, 2023).

Given these theoretical and empirical gaps, the present study aims to investigate the mechanisms through which employees' AI literacy influences green innovation efficiency in Chinese listed firms, with a specific focus on the mediating role of dynamic capabilities and the moderating effect of ESG performance. Accordingly, the study seeks to address the following research questions: (1) To what extent does employees' AI literacy enhance firms' green innovation efficiency? (2) How do dynamic capabilities mediate the relationship between employees' AI literacy and green innovation efficiency? (3) Does ESG performance moderate the direct and indirect effects of employees' AI literacy on green innovation efficiency? and (4) Under what conditions does ESG performance strengthen the transformation of AI literacy into organizational innovation outcomes? By answering these questions, this study contributes to the literature in several ways. It extends green innovation research by incorporating employee-level AI literacy as a key driver, enriches dynamic capability theory by identifying AI literacy as a micro-foundation of organizational capabilities, and advances ESG research by positioning it as a contextual factor that shapes the effectiveness of innovation processes. Ultimately, the findings are expected to provide both theoretical insights and practical implications for firms seeking to enhance green innovation efficiency through the integration of human capital, organizational capability, and sustainability-oriented governance.

Research Objectives

1. To examine the impact of employees' AI literacy on green innovation efficiency and on dynamic capability.

2. To assess the effect of dynamic capability on green innovation efficiency.

3. To analyze the mediating role of dynamic capability in the relationship between employees' AI literacy and green innovation efficiency.

4. To investigate the moderating role of environmental, social, and governance in the relationship between employees' AI literacy and green innovation efficiency.

5. To explore whether environmental, social, and governance moderates the indirect effect of employees' AI literacy on green innovation efficiency through

dynamic capability that is, whether the indirect effect strengthens when environmental, social, and governance is higher.

Research Methodology

1. Research Framework

The research framework was constructed according to the research objectives and hypotheses (Figure 1). This study employs a quantitative research design, utilizing panel data from Chinese A-share listed companies between 2015 and 2021. It systematically examines the impact mechanism of employee AI literacy on green technological innovation efficiency, focusing on the mediating role of corporate dynamic capabilities and the moderating effect of environmental, social, and governance (ESG) factors.

The measurement of variables in this study is based on established literature and authoritative databases. Employee AI literacy indicators were measured through text mining and word frequency analysis. Green technological innovation efficiency was assessed using the ratio of green innovation outputs to innovation inputs. Corporate dynamic capabilities were constructed by standardizing and weighting the average of innovation capacity, absorptive capacity, and adaptive capacity to form a composite dynamic capability index. ESG performance was evaluated using the Huazheng ESG rating system, assigning values (1–9) based on a nine-tier rating scale (C–AAA) to measure corporate ESG levels. Additionally, corporate financial data and patent data primarily originate from the CSMAR database and CNRDS platform, while ESG data is sourced from the Huazheng ESG Rating System. Textual data from corporate annual reports is scraped and processed using Python programs. All data constitutes secondary objective information, involving no personal privacy or ethical risks.

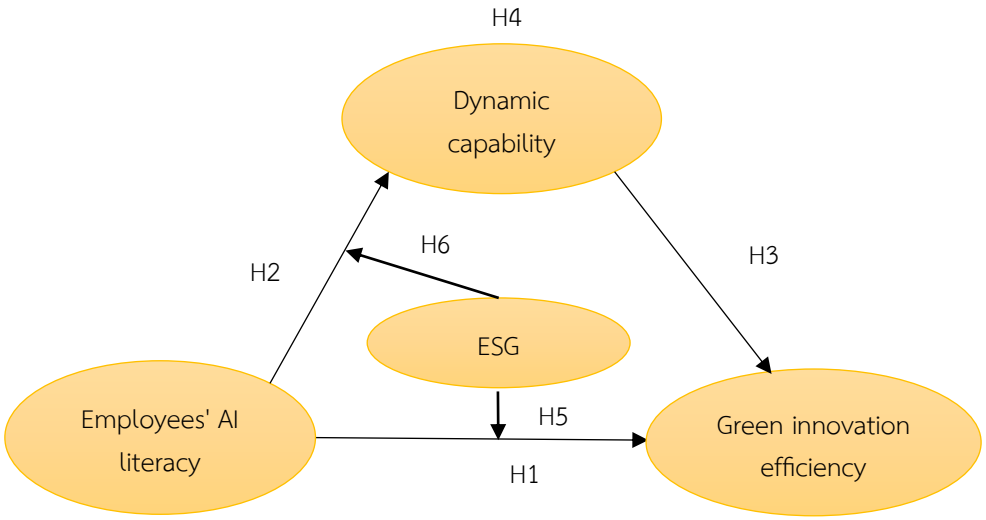

Figure 1 Research framework

2. Sample Selection and Data Sources

The research selects A-share listed firms in China from 2015 to 2021 as the initial sample, applying the following screening criteria: Excluding companies that were labeled as ST, *ST, or PT; had been delisted; were listed in the current year, or had missing key data during the sample period. For continuous variables pertaining to the listed firms, winsorization is applied at the 1% and 99% levels. Firm ESG performance data is sourced from the ESG Rating System, while all other data are obtained from the CSMAR database and the China Research Data Service Platform.

3. Measurement

To examine the relationship between AI literacy and green innovation efficiency, along with the mediating role of dynamic capability and the moderating role of ESG performance, a hierarchical regression model is established. The model specifications are as follows.

$$GIE_{it}=\beta_0+\beta_1 AIL_{it}+\beta_2 X_{it}+\mu_i+\lambda_t+\rho_j+\varepsilon_{it}$$

$$DC_{it}=\phi_0+\phi_1 AIL_{it}+\phi_2 X_{it}+\mu_i+\lambda_t+\rho_j+\varepsilon_{it}$$

$$GIE_{it}=\gamma_0+\gamma_1 AIL_{it}+\gamma_2 DC_{it}+\gamma_3 X_{it}+\mu_i+\lambda_t+\rho_j+\varepsilon_{it}$$

Where GIE_{it} denotes green innovation efficiency, AIL_{it} represents employees' AI literacy, DC_{it} indicates firm dynamic capability, and X_{it} stands for the vector of control variables. μ_t, λ_t, and ρ_j denote industry, year, and province fixed effects, respectively, and ε_{it} is the idiosyncratic error term, based on the established procedure for testing mediation effects:

If β_1 is statistically significant, it indicates that AI literacy significantly enhances green innovation efficiency. If Φ_1 is statistically significant, it suggests a significant positive relationship between AI literacy and dynamic capability. If both Φ_1 and γ_2 are statistically significant, and γ_1 is also significant, it indicates the presence of a partial mediation effect. If both $\Phi 1$ and γ_2 are statistically significant, but γ_1 is not significant, it suggests the presence of a full mediation effect.

4. Moderating the First Stage of the Mediation Pathway

Existing research suggests that ESG performance can also enhance the impact of AI literacy on dynamic capability. Therefore, the moderating variable ESG is incorporated to assess its moderating effect on the relationship between employee AILy and dynamic capability. The model specification is as follows:

$$DC_{it}=\theta_0+\theta_1 \mathrm{AIL}_{it}+\theta_2 ESG_{it}+\theta_3 \mathrm{AIL}_{it}\times ESG_{it}+\theta_4 X_{it}+\mu_i+\lambda_t+\rho_j$$

According to the moderation test logic, the existence of a moderating effect primarily depends on the significance of the interaction term. A significant interaction term indicates the presence of a moderation effect. Therefore, if ϑ_3 is statistically significant, it suggests that ESG exerts a moderating effect on the first stage of the mediation mechanism.

Results

1. Descriptive Statistics and Correlation Analysis

Descriptive statistics for all variables included in the regression analysis are reported in Table 1. The final sample comprises 15,700 firm-year observations from Chinese A-share listed firms covering the years 2015 to 2021.

As shown in the table, the dependent variable, green innovation efficiency (Green1), has a mean of 0.05 (standard deviation = 0.09), with values ranging up to 0.37. The core explanatory variable, AI literacy, exhibits a mean of 1.18 (standard deviation = 1.18) and a maximum value of 14.92.

Variable	M	SD	Minimum	P50	Maximum
GIE	0.050	0.090	0.000	0.001	0.370
AIL	1.180	1.180	0.000	0.760	14.920
DC	0.060	0.220	(0.470)	0.070	0.670
ESG	4.140	1.140	1.000	4.000	8.000
Size	22.240	1.270	19.140	22.070	28.500
Lev	0.400	0.190	0.010	0.390	1.050
ROA	0.040	0.080	(0.800)	0.040	0.880
Growth	0.250	1.790	(0.920)	0.120	96.020
BM	0.950	1.190	0.030	0.610	20.970
Big4	0.050	0.210	0.000	0.000	1.000
Firm age	2.950	0.290	1.610	3.000	4.010

Table 1 Descriptive analysis

2. Regression Analysis

As presented in Table 2, M1 and M2 report the regression results without and with control variables. The results indicate that AI literacy significantly enhances green innovation efficiency at the 1% statistical level, with a coefficient of 0.005. This finding suggests that AI literacy substantially drives the improvement of firm green innovation capability, thus supporting H1.

Variable	(M1)	(M2)
	GIE	GIE
AIL	0.005***	0.005***
	(4.365)	(3.790)
Controls	No	Yes
Industry	No	Yes
Province	No	Yes
Year	No	Yes
Adj R^2	0.137	0.173
F	19.055***	21.682***
Observation	15700	15700

Table 2 Baseline regression results

3. Alternative Measures of the Core Explanatory Variable

Second, the core explanatory variable is modified. We employ two alternative measures: 1) the natural logarithm of one plus the AI-related word frequency

(denoted as AIL_Y), and 2) the one-period lagged value of the original digital transformation variable [denoted as AIL (-1)]. The regression results, presented in Table 3, demonstrate that the positive impact of AI literacy on green innovation efficiency remains robust. These findings are consistent with the baseline regression results.

Variable	(M1)	(M2)
	GIE	GIE
AIL_Y	0.005*** (3.482)	/
AIL (-1)	/	0.006*** (3.755)
Controls	Yes	Yes
Industry	Yes	Yes
Province	Yes	Yes
Year	Yes	Yes
Adj R^2	0.173	0.177
F	21.709***	20.842***
Observation	15700	13114

Table 3 Regression results with alternative measures of the core explanatory variable

4. Mediating Effects

As shown in Table 4, column (M1) presents the baseline regression results. Column (M2) uses dynamic capability as the dependent variable. The results in column (M2) indicate that dynamic capability are significantly and positively influenced by AI literacy at the 1% level. Column (M3) uses green innovation efficiency as the dependent variable and includes the mediator (dynamic capability). The regression results show that the coefficient of AI literacy on green innovation efficiency is not significant, while dynamic capability has a significantly positive effect on green innovation efficiency at the 10% level. Therefore, these findings suggest that dynamic capability plays a partial mediating role in the relationship between AI literacy and green innovation efficiency, supporting H2, 3, and 4.

Variable	(M1)	(M2)	(M3)
AIL	GIE 0.005*** (3.790)	DC 0.010*** (4.400)	GIE -0.001 (-0.771)
DC	/	/	0.005*** (-0.771)
Controls	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Province	Yes	Yes	Yes
Year	Yes	Yes	Yes
Adj R^2	0.173	0.177	0.663
F	21.682***	22.233***	0.969***
Observation	15700	15624	15625

Table 4 Mediating effects

5. Moderating Effect of ESG

M1 in Table 5 includes the explanatory variable (AI literacy), the moderating variable (ESG), and their interaction term to test the moderating effect of ESG performance on the direct path. The results show that the coefficient of the AI literacy * ESG interaction term is significantly positive at the 5% level, supporting H5.

6. Testing the Moderating Effect of ESG on the Mediation Pathway

We further test the moderating effect of ESG on both stages of the mediation pathway (i.e., the effect of AI literacy on dynamic capability, and the effect of dynamic capability on green innovation efficiency). The results are presented in Columns (M2) and (M3) of Table 5.

Column (M2) shows that the interaction term between AI literacy and ESG is significantly positive at the 5% level. This indicates that ESG performance exerts a positive moderating effect on the relationship between AI literacy and dynamic capability, thus supporting H6.

Column (M3) shows that the coefficient of the interaction term between dynamic capability and ESG is significantly positive at the 10% level. This confirms the existence of a moderating effect based on the mediating role of dynamic capability, providing further evidence in support of H6.

Variable	(M1)	(M2)	(M3)
	GIE	DC	GIE
AIL	0.004***	0.009***	0.004***
	(3.790)	(4.253)	(3.368)
DC	/	/	0.016***
			(4.321)
ESG AIL	0.002**	0.003**	0.002*
	(2.052)	(2.331)	(1.817)
ESG	0.008***	0.006***	0.008***
	(7.985)	(3.304)	(7.892)
ESG × DC	/	/	0.004
			(1.349)
Controls	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Province	Yes	Yes	Yes
Year	Yes	Yes	Yes
Adj R^2	0.182	0.138	0.184
F	21.556***	19.775***	19.002***
Observation	15527	15494	15494

Table 5 Regression results for the moderating effect of ESG based on the mediating role of dynamic capability

7. Heterogeneity Analysis

To examine how the impact of dynamic capability on green innovation efficiency varies across regions, we split the sample into three subsamples based on geographical location: Eastern, Central, and Western China. The results of the subsample regressions are presented in Columns (M3), (M4), and (M5) of Table 6.

Column (M3) reports that for firms in the Eastern region, the coefficient of dynamic capability on green innovation efficiency is 0.004 and is significantly positive at the 1% level. Similarly, Column (M4) shows that for firms in the Central region, the corresponding coefficient is 0.007 and is also significantly positive at the 1% level. In contrast, the coefficient for the Western region is statistically insignificant.

These results indicate that the effect of dynamic capability on green innovation efficiency is contingent upon regional context. A plausible explanation lies in the disparities in regional economic development, environmental pressure, regulatory stringency, industrial structure, and technological advancement across

China. Firms located in the more developed Eastern and Central regions, which typically face greater environmental demands and possess stronger technological foundations, may therefore exhibit a more pronounced effect of dynamic capability on driving green innovation efficiency.

Variable	(M1) GIE	(M2) GIE	(M3) GIE
DC	0.004*** (3.142)	0.007** (2.283)	0.000 (0.123)
Controls	Yes	Yes	Yes
Industry	Yes	Yes	Yes
Province	Yes	Yes	Yes
Year	Yes	Yes	Yes
Adj R^2	0.169	0.245	0.189
F	15.091***	6.008***	3.550***
Observation	11491	2411	1753

Table 6 Heterogeneity regression results

Discussion

The findings of this study demonstrate that employees' AI literacy plays a direct and significant role in enhancing green innovation efficiency, echoing prior evidence that AI literacy improves firm-level innovation performance (Li & Chen, 2020). Employees equipped with stronger AI-related skills can more effectively utilise intelligent tools and data-driven analytics, thereby reducing resource waste and improving the efficiency of green R&D processes. This suggests that under China's accelerating AI literacy and low-carbon transition, human technology integration has become an essential internal driver of green innovation.

Further analysis confirms that dynamic capability constitutes an important mechanism through which AI literacy translates into green innovation outcomes. Employees with higher AI literacy exhibit stronger innovation, absorptive, and adaptive capacities, enabling firms to better identify, integrate, and reconfigure resources in response to policy and market uncertainties. This finding extends dynamic capability theory by showing that employee-level technological literacy functions as a micro-foundation that strengthens firms' adaptive mechanisms, thereby sustaining green innovation performance in complex external environments.

Moreover, the moderating and moderated mediation effects of ESG performance indicate that an organisational environment characterised by strong sustainability orientation, governance transparency, and social responsibility can amplify the value of AI literacy. Consistent with Eccles, et al. (2014), firms with stronger ESG foundations more effectively convert employees' AI capabilities into dynamic capability, thus improving green innovation output. ESG serves as a critical contextual enabler that enhances the translation of technological literacy into sustainable innovation performance.

New Knowledge

This study generates new knowledge by demonstrating how employees' AI literacy acts as a critical driver of green innovation efficiency in Chinese firms. It reveals a multi-path mechanism in which AI-literate employees enhance firms' dynamic capability innovation, absorptive, and adaptive capacities thereby improving green innovation outcomes. The study also identifies ESG performance as a positive boundary condition, strengthening both the direct and indirect effects of AI literacy. Moreover, the discovery of regional disparities provides contextual insight into how institutional and economic environments shape the effectiveness of AI-related competencies. Together, these findings enrich the literature by integrating human capital, dynamic capability theory, and sustainability frameworks into a unified explanatory model.

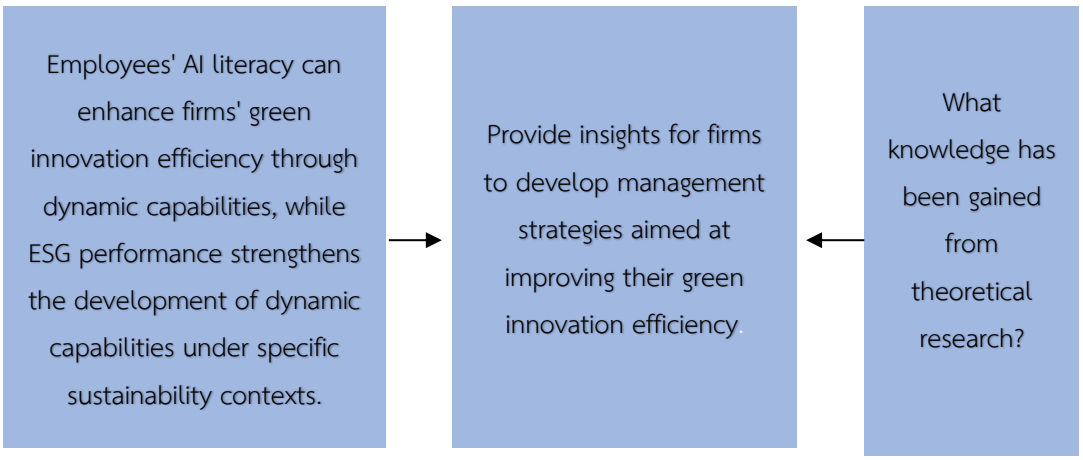

Figure 2 New Knowledge

Strengthening employees' AI literacy through targeted capability development, dynamic capability building, and ESG-oriented governance will effectively enhance firms' green innovation efficiency.

Conclusion and Suggestion

This study demonstrates that employees' AI literacy substantially enhances the efficiency of green innovation, both directly and by strengthening firms' dynamic capability. The findings further confirm that ESG performance amplifies these effects by providing a governance and value environment that enables AI competencies to translate more effectively into green innovation outcomes. At the same time, regional analyses reveal clear disparities, with central regions exhibiting the strongest impact. These results collectively extend the understanding of how technological capabilities, organizational mechanisms, and contextual conditions jointly shape green innovation performance.

To promote the effective transformation of AI literacy into sustainable innovation, firms should prioritise long-term investment in employee AI training and strengthen dynamic capability through targeted R&D incentives and knowledge collaboration. Moreover, building an organisational climate grounded in strong ESG principles can better channel technological capacity into green outcomes. Finally, addressing regional imbalances through differentiated capacity-building strategies and cross-regional cooperation will support more equitable advancement of green innovation nationwide.

1. Limitations and Future Directions

1.1 The use of panel data allows only for the identification of correlations and is susceptible to unobserved confounding factors, making it difficult to establish causal relationships. Future studies may adopt quasi-experimental methods—such as policy shocks, instrumental variables, or difference-in-differences (DID)—to achieve more robust causal inference.

1.2 The sample is restricted to Chinese A-share listed firms, which limits the applicability of the findings to other countries or institutional settings. Future research could conduct cross-country comparisons or examine contexts with different ESG regimes, digital infrastructures, and environmental regulatory pressures to enhance external validity.

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